MAGNETIC & ELECTROMAGNETIC TRANSDUCERS

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Stanford University

MAGNETIC TRANSDUCERS

- Magnetic field sensors
- Current sensors
- Angle sensors
- Magnetometers
- Magentic read/write heads
- Micromachined inductors
- Magnetic actuators
- Others...

EXAMPLE MAGNETIC FLUX DENSITIES (B)

Calculated magnetic flux at the surface of a neutron star.	100 MT
Magnetic flux produced by the strongest superconducting electromagnets.	40 to 60 T
Magnetic flux produced by the strongest conventional electromagnets.	4 to 6 T
Magnetic flux near a small bar magnet.	10 mT
Magnetic storage media.	≈ 1 mT
Earth's magnetic flux at near equatorial latitude.	≈ 100 μT
Limit in magnetic flux below which superconducting quantum interference detector (SQUID) or specialized flux-gate magnetometers are typically required.	10 to 100 nT
Magnetic flux produced by electrical currents in the human heart.	10 nT
Magnetic flux in interstellar space.	100 pT
Magnetic flux produced by our galaxy.	1 pT
Lowest magnetic flux achievable in carefully shielded room.	10 fT

RELATIVE PERMEABILITIES

Material	Relative Permeability (μ_r)
Mercury	0.999968
Silver	0.9999736
Copper	0.9999906
Water	0.9999912
Air	1.00000037
Tungsten	1.00008
Platinum	1.0003
Nickel-Zinc Ferrite	650
Manganese-Zinc Ferrite	1,200
Permalloy (78.5% Ni, 21.5% Fe)	70,000
Iron (99.96% pure)	280,000
“Supermalloy” (79% Ni, 15% Fe, 5% Mo, 0.5% Mn)	1,000,000

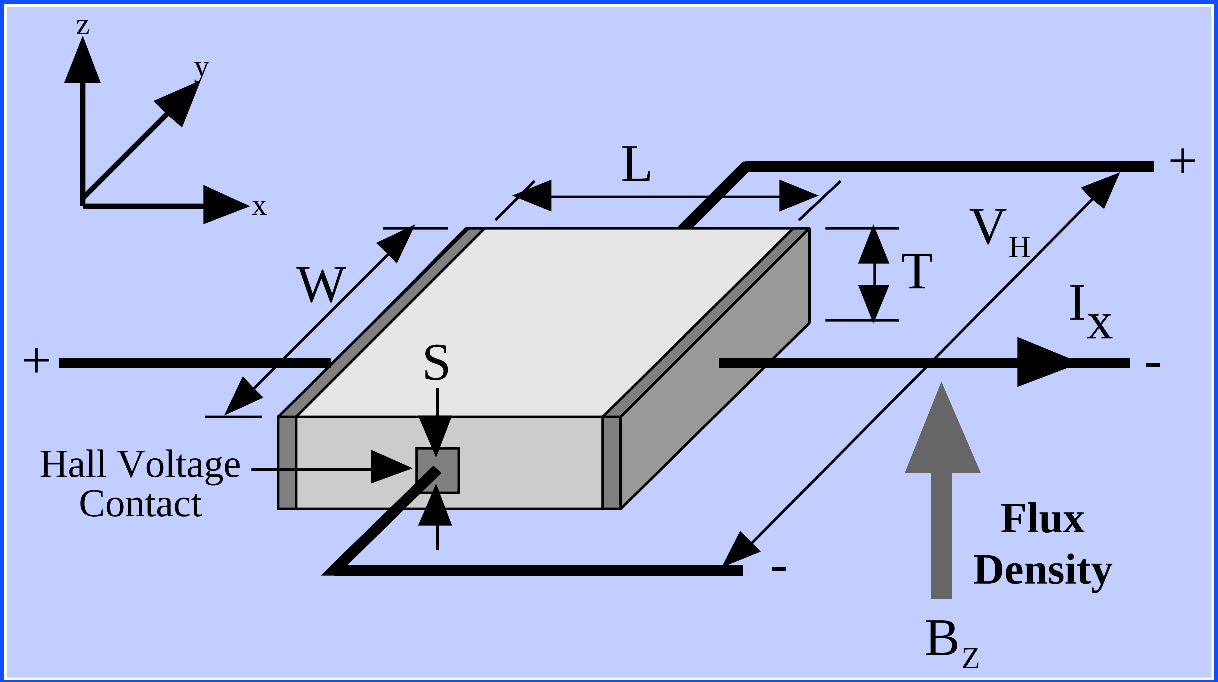
Reference: Bate, G., “Magnetism,” in Chapter 34, “Magnetism and Magnetic Fields,” in “The Electrical Engineering Handbook,” Dorf, R. C. [ed.], CRC Press, Inc., Boca Raton, FL, 1993, pp. 811 - 826.

- *Magnetic flux density* (or magnetic induction), B, is expressed in teslas (T = (N•s)/(C•m), N/(A•m), or 1 Weber/m^2 [Wb/m2]). The gauss, a non-SI unit that is still commonly used, is simply 10^{-4} T.
- *Magnetic field strength* (or magnetic field intensity), H, has units of A/m. An older unit is the Oersted (Oe) where one A/m = 1.257 ∞ 10^{-2} Oe.
- The relative permeability, μ_r, of a material is essentially a measure of how conductive it is to magnetic fields. It relates B and H together by,

$$\mu = \mu_o \mu_r = \frac{B}{H}$$

THE HALL EFFECT

- **Hall effect: charge carriers travelling in a magnetic field are subject to a deflection by the Lorentz Force. If the carriers are flowing in a slab of metal or semiconductor, they are deflected preferentially to one side of the slab.**



$$\vec{F} = -q\left(\vec{v} \times \vec{B}\right)$$

$$V_H = \frac{R_H I_X B_Z}{T} = R_H J_X W B_Z$$

Reference: Middelhoek, S. and Audet, S. A., "Silicon Sensors," Academic Press, London, U.K., 1989.

HALL EFFECT DETAILS

- As shown in the previous diagram, electrons are deflected in the negative y direction (holes in the +y direction in a semiconductor), building up charge near the Hall plates.
- The built-up electric charge balances the Lorentz force (electrons travel straight through) in ≈ 10^{-14} seconds.
- The Hall voltage is directly proportional to the current flowing through the slab and inversely proportional to the thickness of the slab.
- The material-dependent Hall constant, R_H, is between 4 and 5 orders of magnitude larger for silicon than most metals.
- The Hall constant is inversely proportional to the carrier density, explaining why semiconductors make good Hall sensors.

$$R_{H(electrons)} = -\frac{r}{nq}$$ In cm^3/C

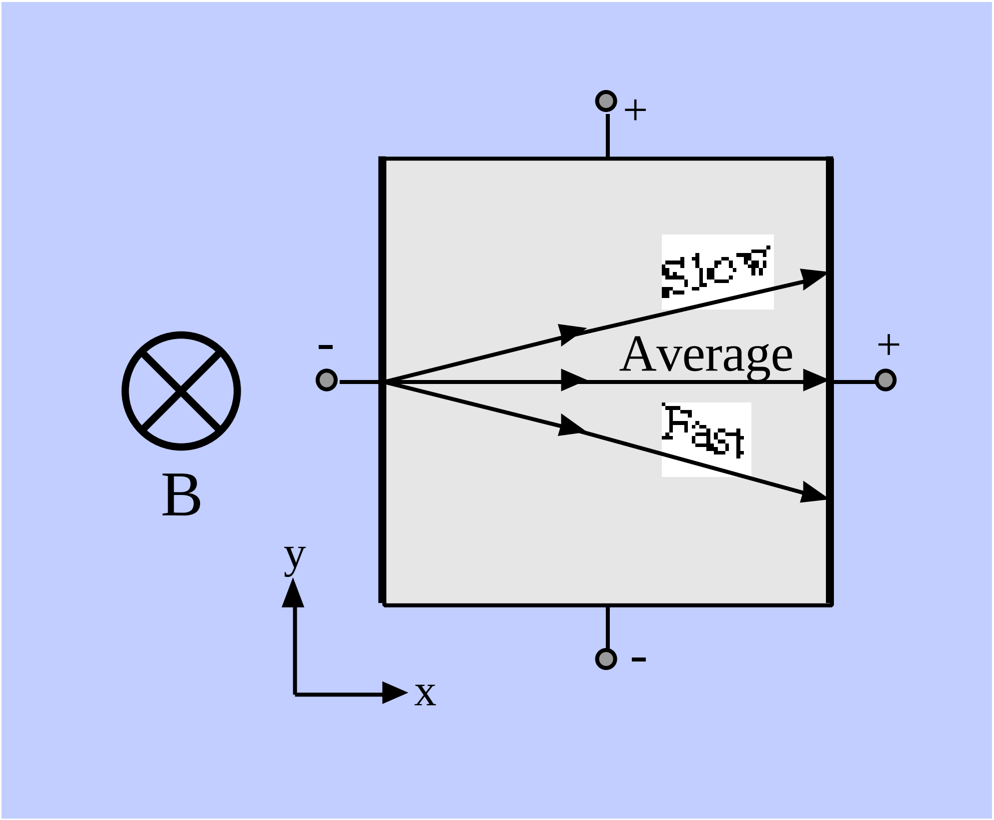
$$R_{H(holes)} = +\frac{r}{pq}$$ In cm^3/C

HALL EFFECT BOTTOM LINES

- **The *Hall voltage is proportional to the drive current*, but if you want high sensitivity without high power, one needs to optimize other parameters.**
- **The *Hall voltage is very linearly related to the magnetic flux density*, B, (typically < 1% nonlinearity).**
- **The *Hall voltage is inversely proportional to the plate thickness* -> try to make it as thin as possible, e.g. a doped well.**
- **The *Hall voltage is inversely proportional to the carrier density* – that is why the Hall Effect is greater in semiconductors than in metals.**
- **There is a value of p-type doping at which R_H becomes zero, so regions of silicon can be made insensitive to magnetic field.**

PHYSICAL MAGNETORESISTIVE EFFECT

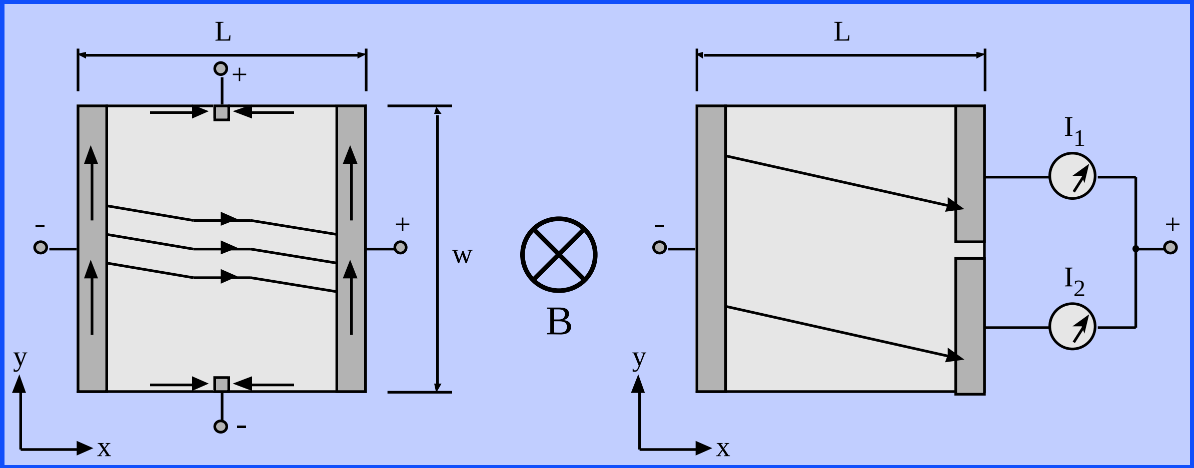
- Carriers have different drift velocities and hence are deflected varying amounts by the Lorentz force.
- Paths other than straight have higher effective resistances.
- This effect is negligible in silicon, but not in InSb (μ_n=80,000 cm^2/V•s) and GaAs.
- Thin-film devices can be constructed that use this effect to obtain nanosecond responses.



Reference: Middelhoek, S. and Audet, S. A., “Silicon Sensors,” Academic Press, London, U.K., 1989.

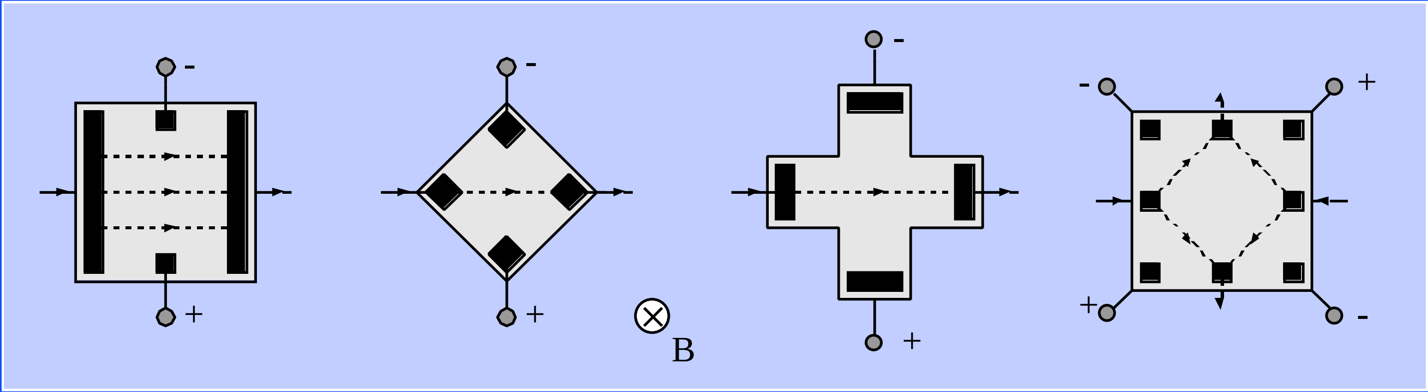
GEOMETRICAL MAGNETORESISTIVE EFFECT

- For short (small L) Hall plates, the current input contacts tend to short out the Hall voltage (as shown).
- This effect shows up as an effective resistance that is nonlinearly related to the magnetic field.
- The idea is to deliberately short-circuit as much of the Hall voltage as possible.
- One can stack multiple thin Hall plates (L<<W) for more sensitivity.

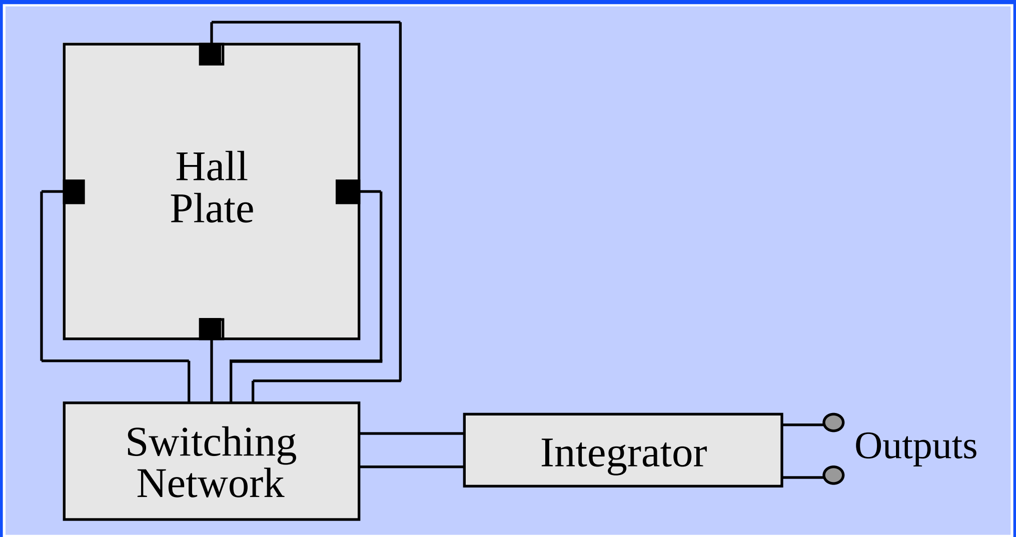


Reference: Middelhoek, S. and Audet, S. A., "Silicon Sensors," Academic Press, London, U.K., 1989.

HALL PLATE DESIGNS

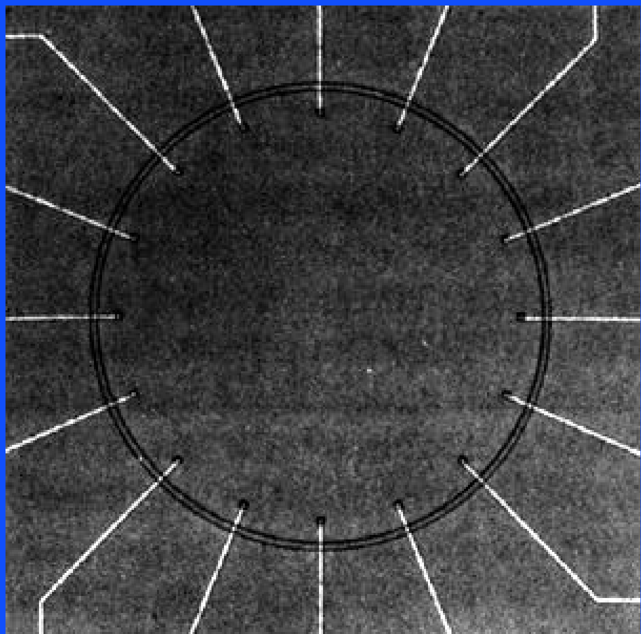


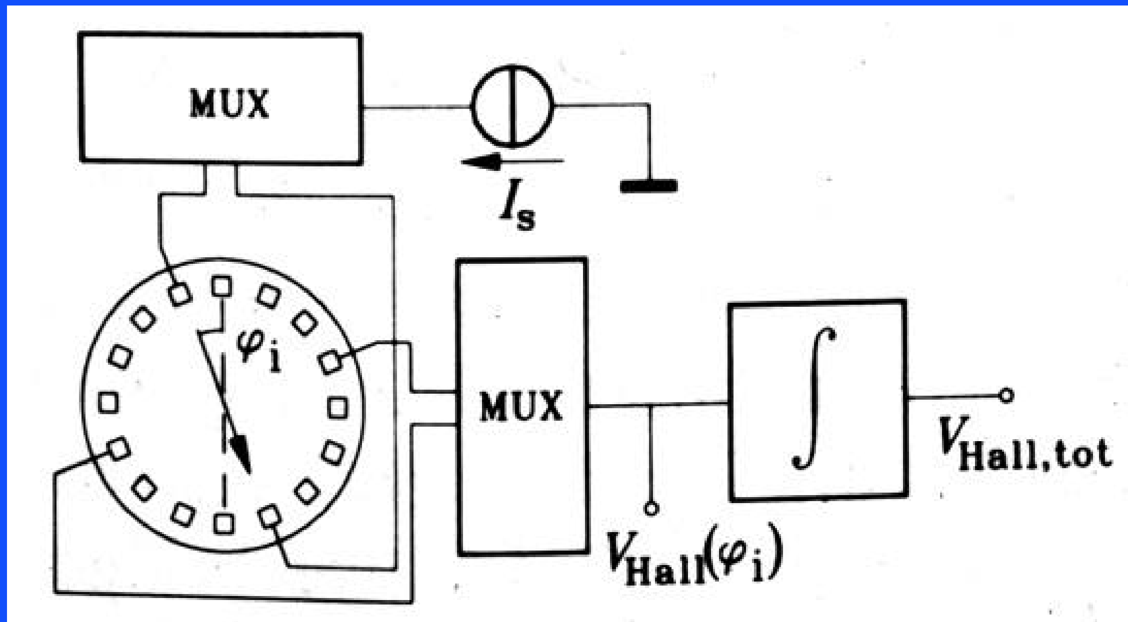
Reference: Middelhoek, S. and Audet, S. A., "Silicon Sensors," Academic Press, London, U.K., 1989.



Reference: Maupin, J. T. and Geske, M. L., "The Hall Effect in Silicon Circuits," in "The Hall Effect and its Applications, Chien, C. L. and Westgate, C. R., Eds, Plenum Press, New York, NY, 1980, pp. 421 - 445.

OFFSET NULLING VIA ROTATING ELECTRODES

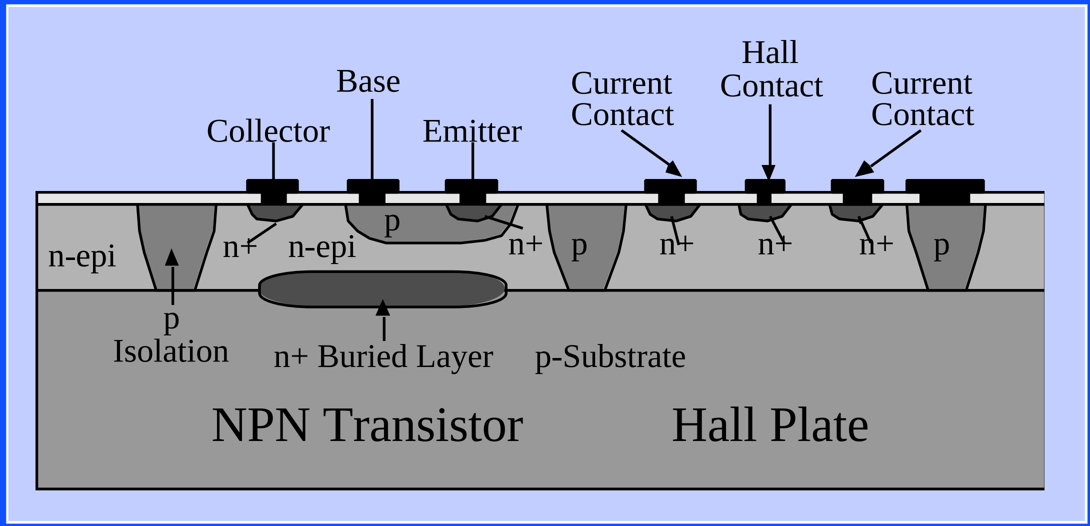




Sources: Munter, P. J. A., "A Low-Offset Spinning Current Hall Plate," Sensors and Actuators, vol. A22, nos. 1 - 3, Mar. 1990, pp. 743 - 746, and Munter, P. J. A., "Electronic Circuitry for a Smart Spinning-Current Hall Plate with Low Offset," Sensors and Actuators, vol. A27, nos. 1 - 3, May 1991, pp. 747 - 751.

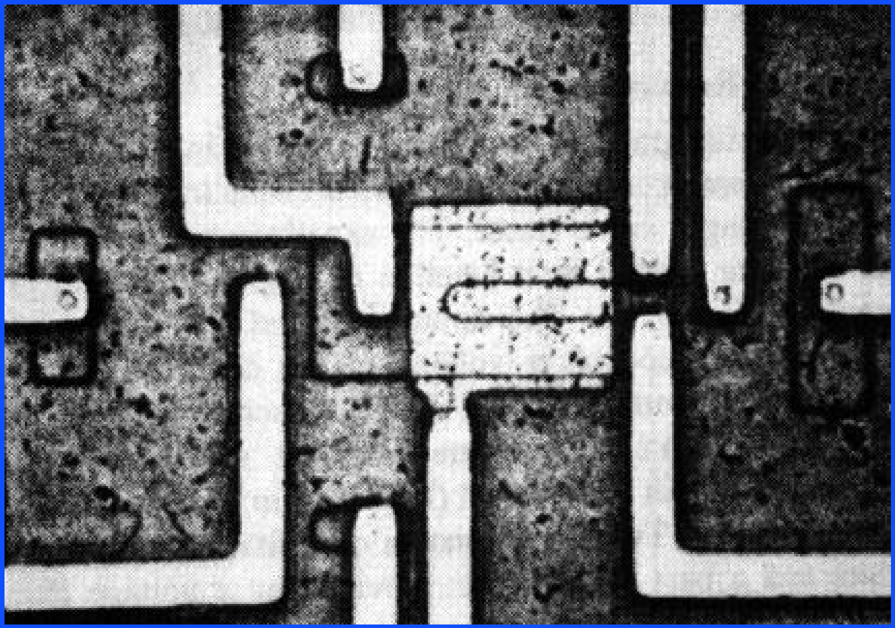
HALL PLATES IN SEMICONDUCTOR PROCESSES

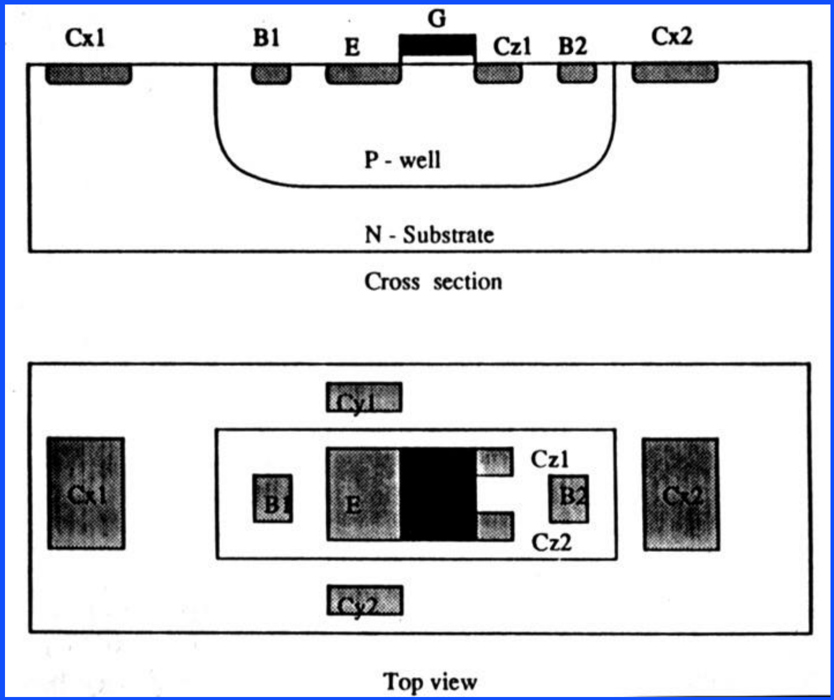
- **Hall plates and magnetically sensitive active devices are available "inherently" in active circuit processes.**
- **In bipolar processes, the lower-doped n-type collector regions are often used as Hall plates since the lower carrier concentration and higher mobilities increase the sensitivity.**



Reference: Middelhoek, S. and Audet, S. A., "Silicon Sensors," Academic Press, London, U.K., 1989.

EXAMPLE HALL DEVICE IN SILICON



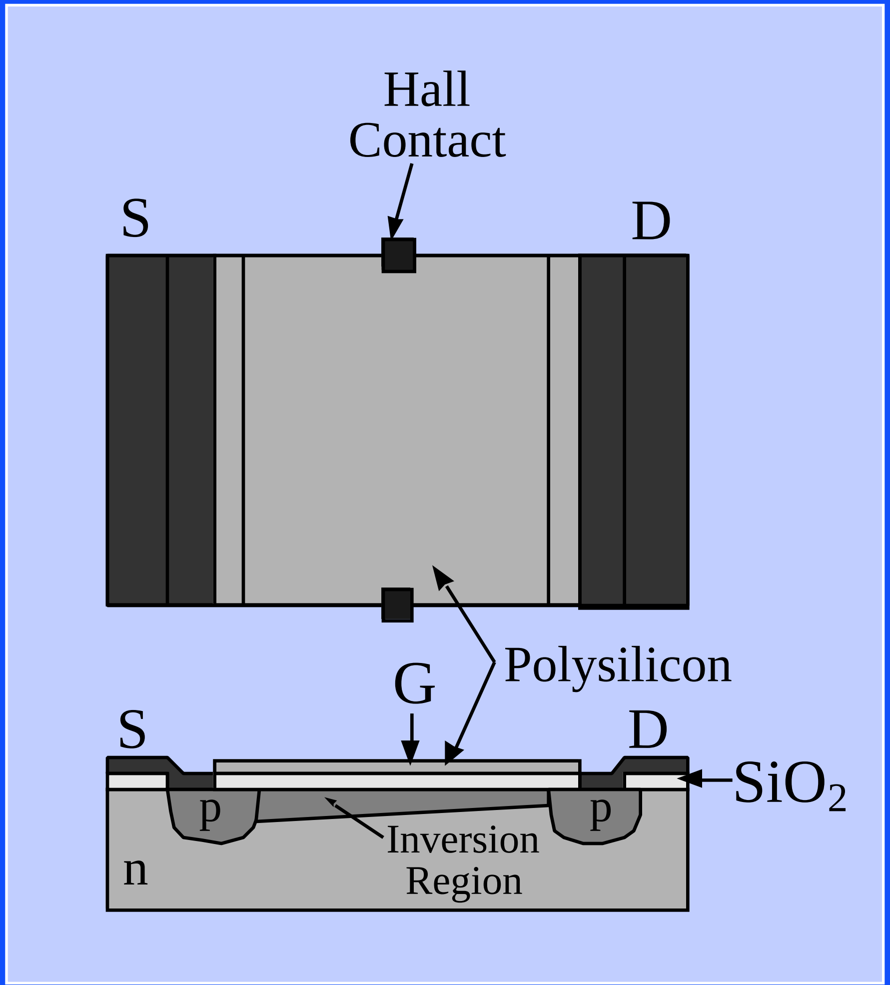


Source: Zhang, M., and Misra, D., "A Novel 3-D Magnetic Field Sensor in Standard CMOS Technology," Proceedings of Transducers '91, the 1991 International Conference on Solid-State Sensors and Actuators, San Francicso, CA, June 24 - 27, 1991, pp. 1085 - 1088.

MOS HALL PLATES

- Here the Hall plate is the inversion region in the active region of the MOSFET and hence its thickness (and sensitivity) can be electrically modulated.
- Two contacts are added along the sides of the active region.

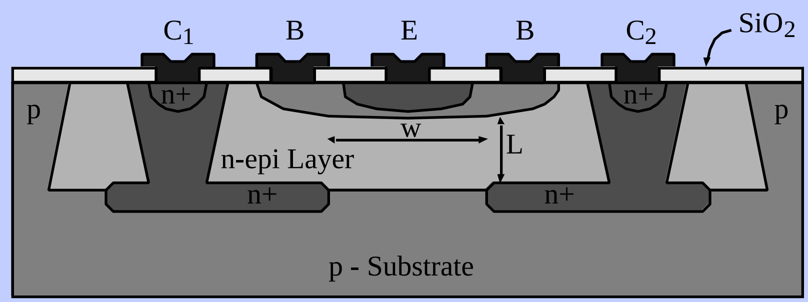
$$V_H = \frac{IB}{C_{OX}\left(V_{GS} - V_T\right)}$$



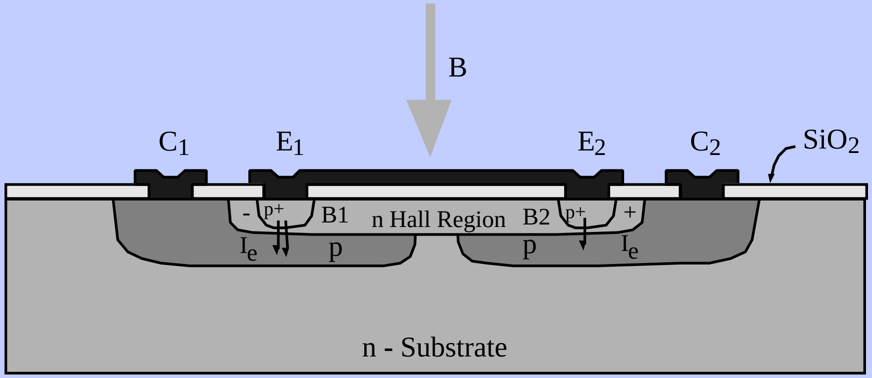
Reference: Middelhoek, S. and Audet, S. A., “Silicon Sensors,” Academic Press, London, U.K., 1989.

MAGNETOTRANSISTORS

- These devices are essentially Hall plates directly merged with bipolar or MOS transistors.
- Multiple collectors or drains are used, and currents to each are determined by how carriers are deflected by the Lorentz force.
- Bipolar devices can be lateral or vertical, and MOS devices are generally lateral.
- A Hall plate can be merged with the bases of a differential pair, providing built-in gain.



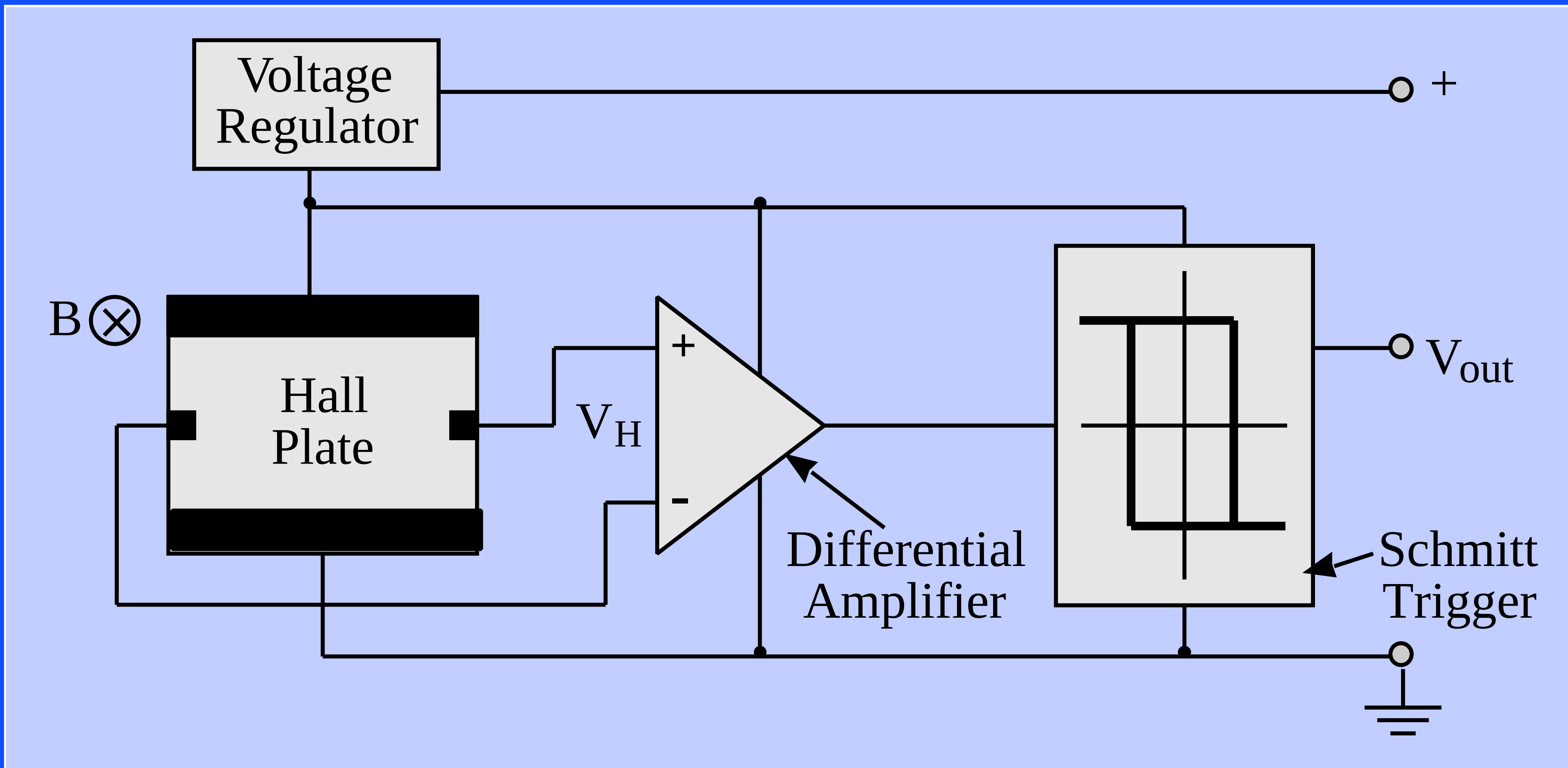
Vertical NPN magnetotransistor.



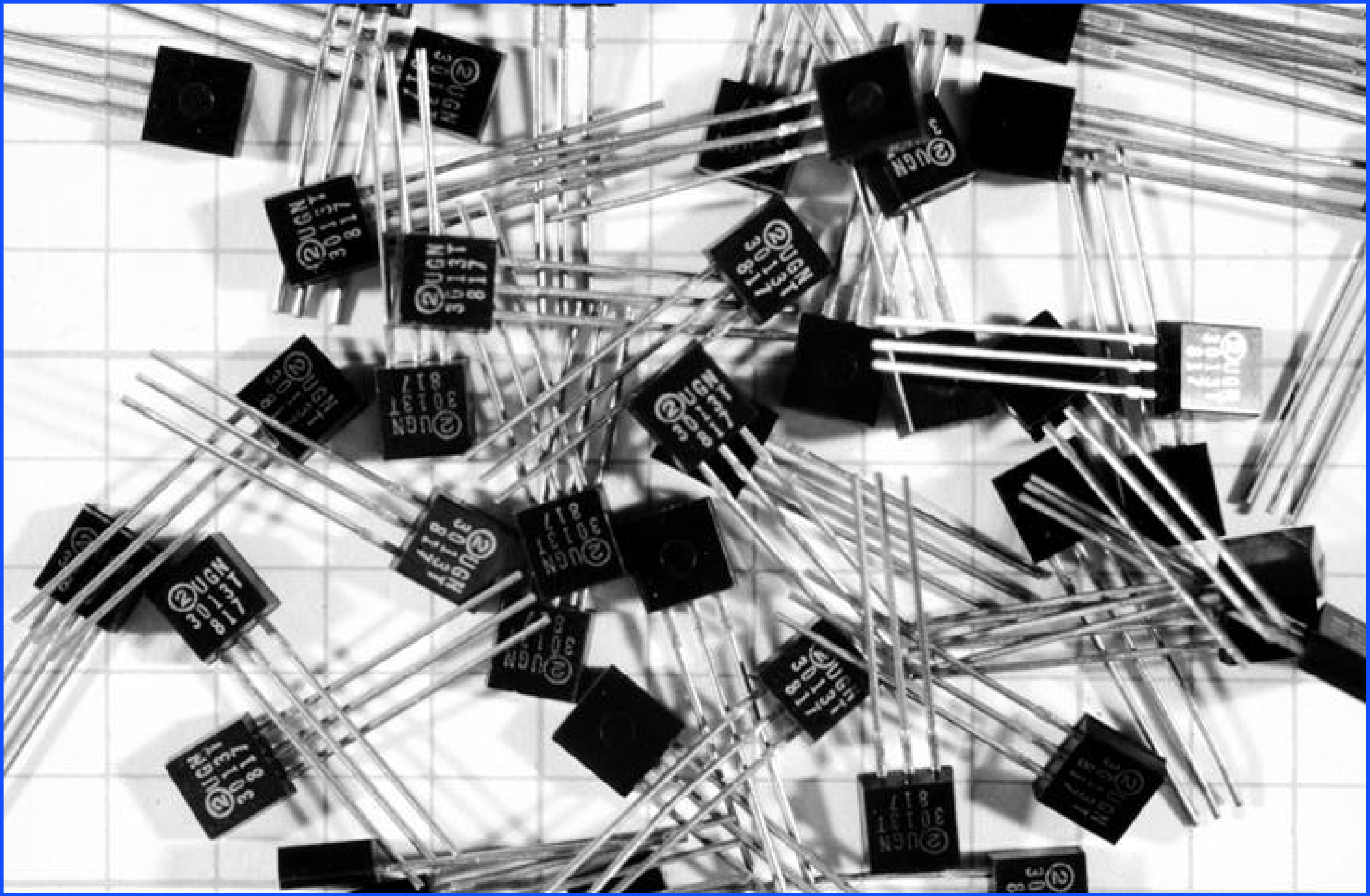
Differential PNP magnetotransistor pair.

Reference: Middelhoek, S. and Audet, S. A., “Silicon Sensors,” Academic Press, London, U.K., 1989.

COMMERCIAL HALL DEVICES



Reference: Allegro Microsystems data book, Allegro Microsystems, Worcester, MA.



Hall effect devices courtesy of Sprague, Inc. (this division is now Allegro).

FLUX-GATE MAGNETOMETERS

- **The inductance of a solenoid is related to its magnetic permeability, which is in turn nonlinearly dependent upon the applied magnetic field.**
- **If the solenoid is biased into a high-slope (high μ) region of the B-H curve, its inductance will be extremely sensitive to external magnetic fields.**

$$L = \frac{\mu_o \mu_r N^2 A}{l}$$

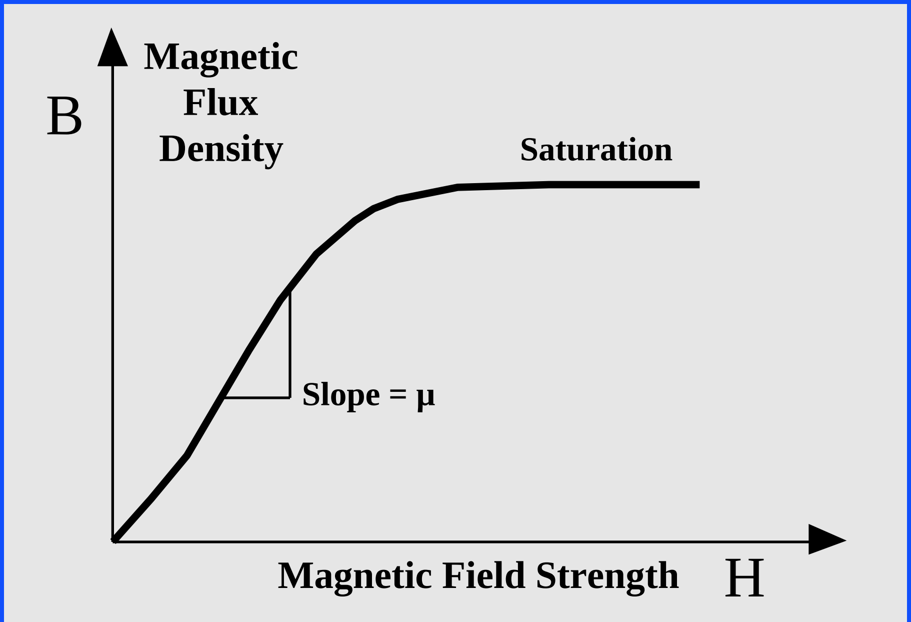
μ_o = magnetic permeability of free space = $4\pi \times 10^{-7}$ T•m/A

μ_r = relative magnetic permeability of the solenoid core

N = number of turns of conductor in solenoid

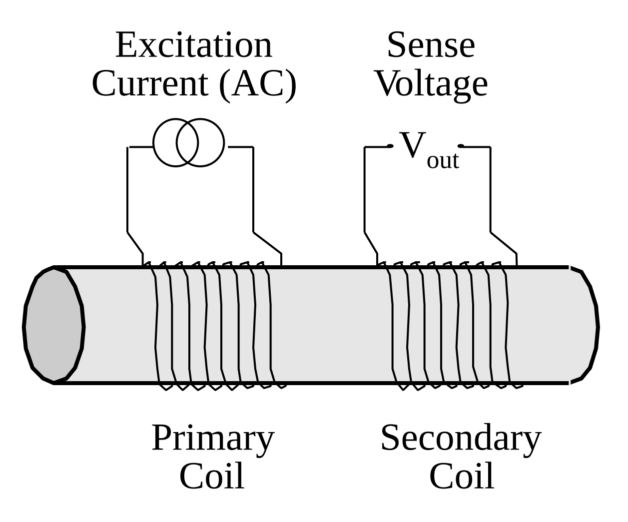
A = cross-sectional area of solenoid

l = length of solenoid over which conductor turns are arranged



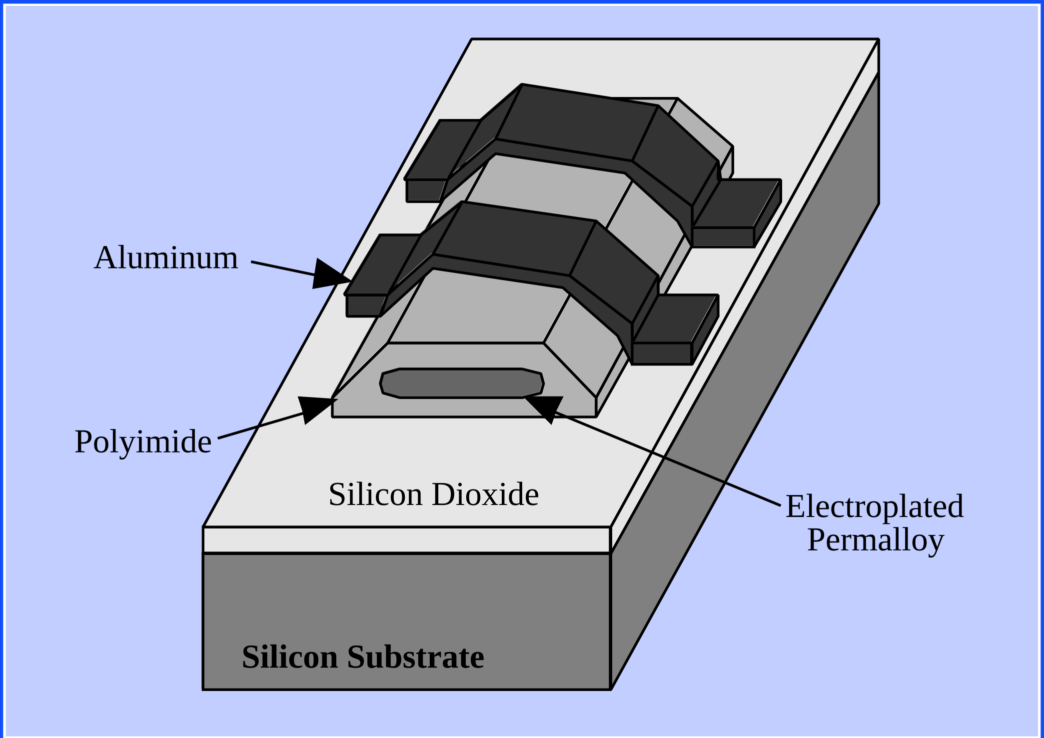
FLUX-GATE MAGNETOMETER OPERATION

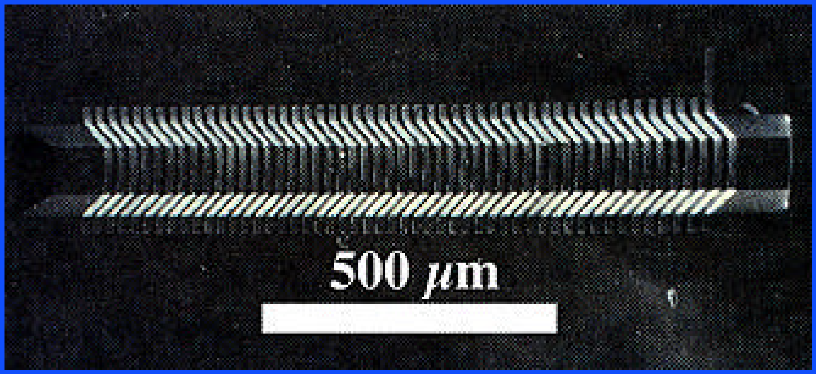
- Can measure the inductance of a solenoid directly (e.g. tuned circuit).
- A solenoid transformer can be fabricated, and the coupling (or harmonic generation due to the nonlinearity).
- The transformer approach is most commonly used.
- Due to the frequency dependence of core permeability, higher frequency operation can often improve sensitivity (although parasitic capacitances and increased power dissipation can be a problem).



Reference: Kawahito, S., Choi, S. O., Ishida, M., and Nakamura, T., "MOS Hall Elements with Three-Dimensional Microstructure," Proceedings of Transducers '93, the 7th International Conference on Solid-State Sensors and Actuators, Yokohama, Japan, June 7 - 10, 1993, Institute of Electrical Engineers, Japan, pp. 892 - 895.

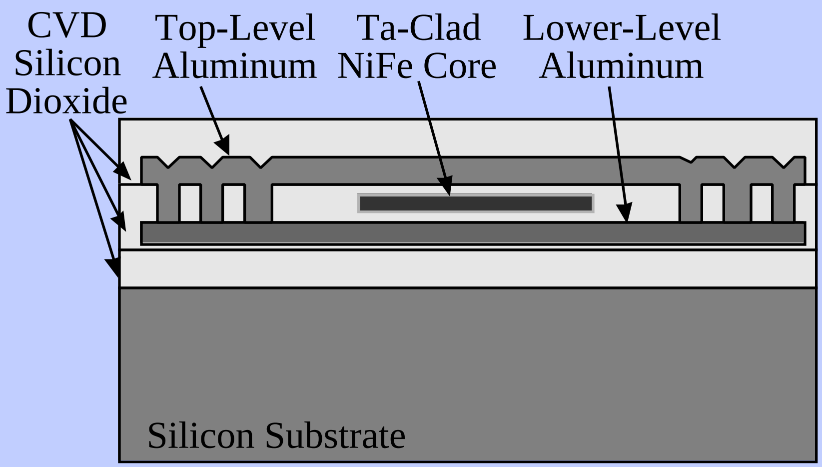
MICROMACHINED SOLENOIDS



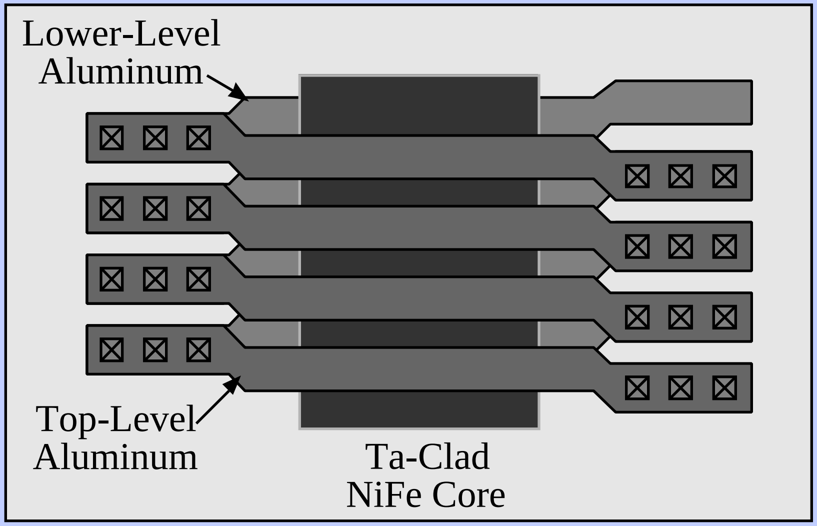


Reference: Kawahito, S., Choi, S. O., Ishida, M., and Nakamura, T., "MOS Hall Elements with Three-Dimensional Microstructure," Proceedings of Transducers '93, the 7th International Conference on Solid-State Sensors and Actuators, Yokohama, Japan, June 7 - 10, 1993, Institute of Electrical Engineers, Japan, pp. 892 - 895.

MICROMACHINED SOLENOIDS IN CMOS



Side View

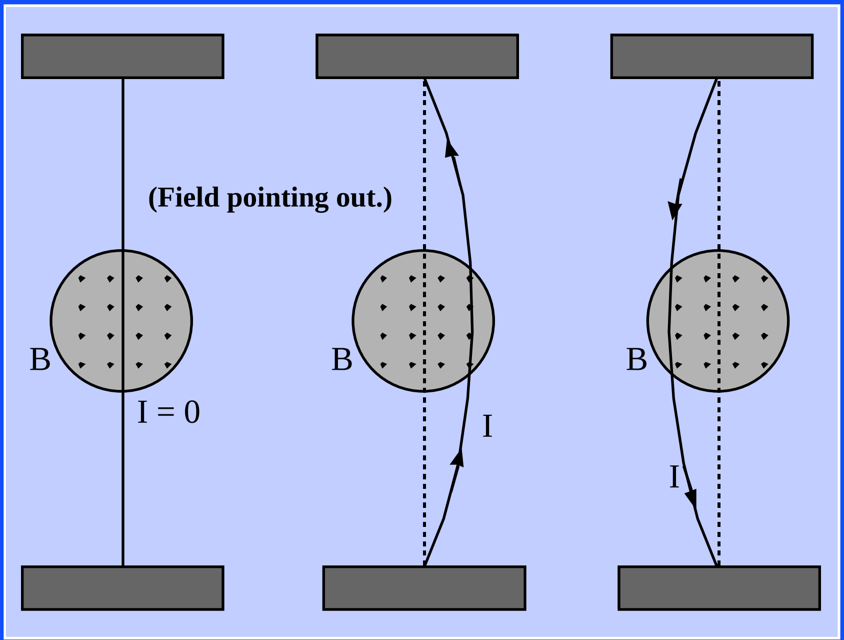


Top View

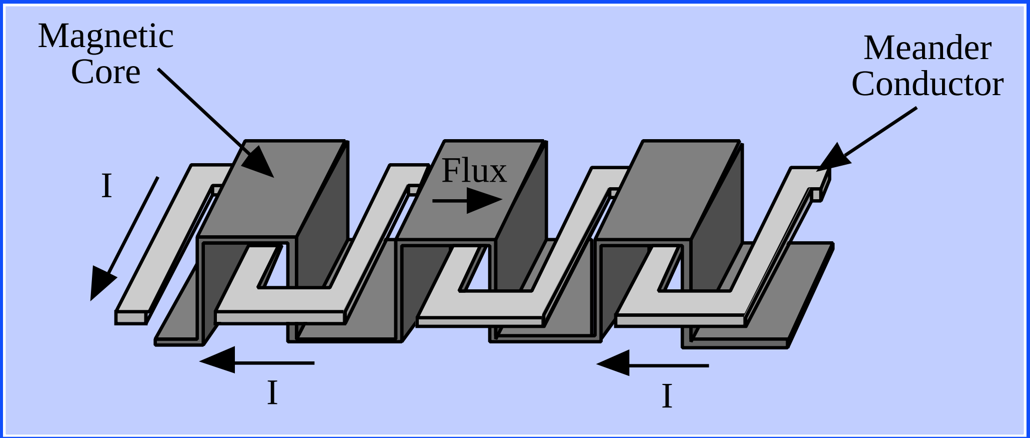
Gottfried-Gottfried, R., Budde, W., Jähne, R., Kück, H., Sauer, B., Ulbricht, S., and Wende, U., "A Miniaturized Magnetic Field Sensor System Consisting of a Planar Fluxgate Sensor and a CMOS Readout Circuitry," Digest of Technical Papers, Transducers 95, Stockholm, Sweden, June 25 - 29, 1995, vol. 2, pp. 229 - 232.

MAGNETIC ACTUATION

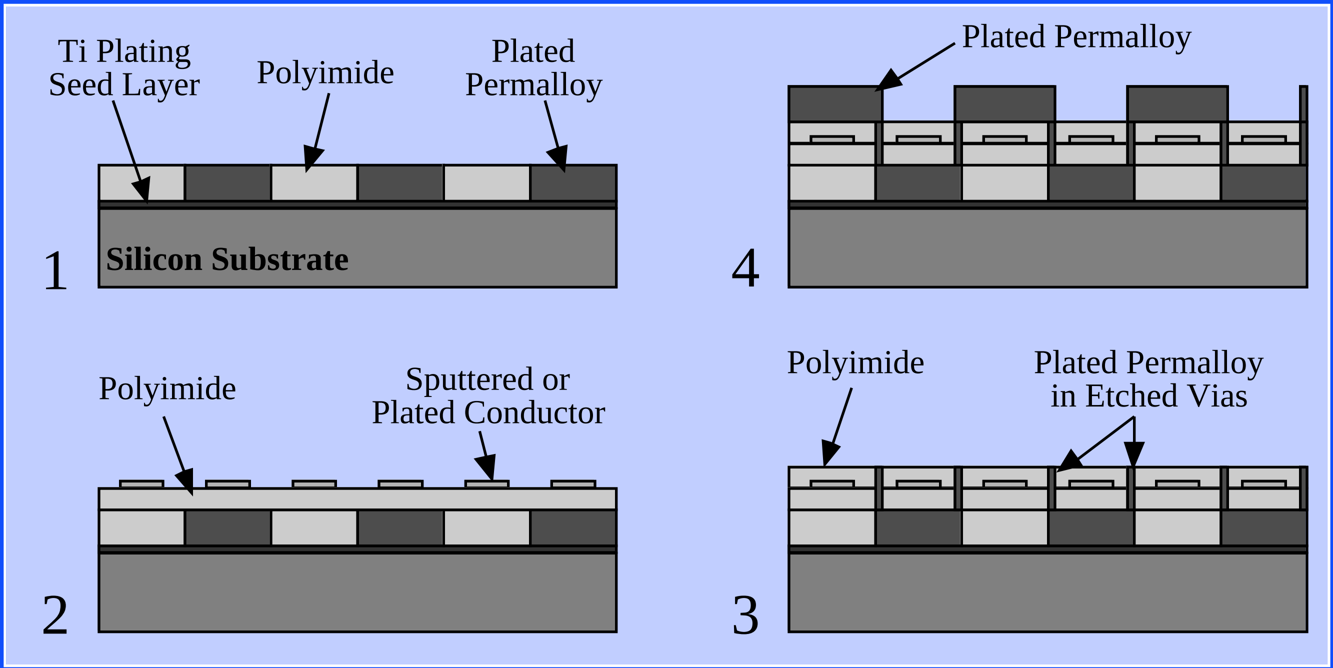
- Magnetic field actuators rely on attraction or repulsion of magnetic fields (generated by currents or permanent magnets).
- Such devices are used extensively in micromachined actuators and are relatively simple to implement.
- Magnetostrictive actuators (little used in micromachined devices at present) rely on shortening of materials such as Terfenol ($TbFe_2$) can generate peak strains on the order of 0.2%.



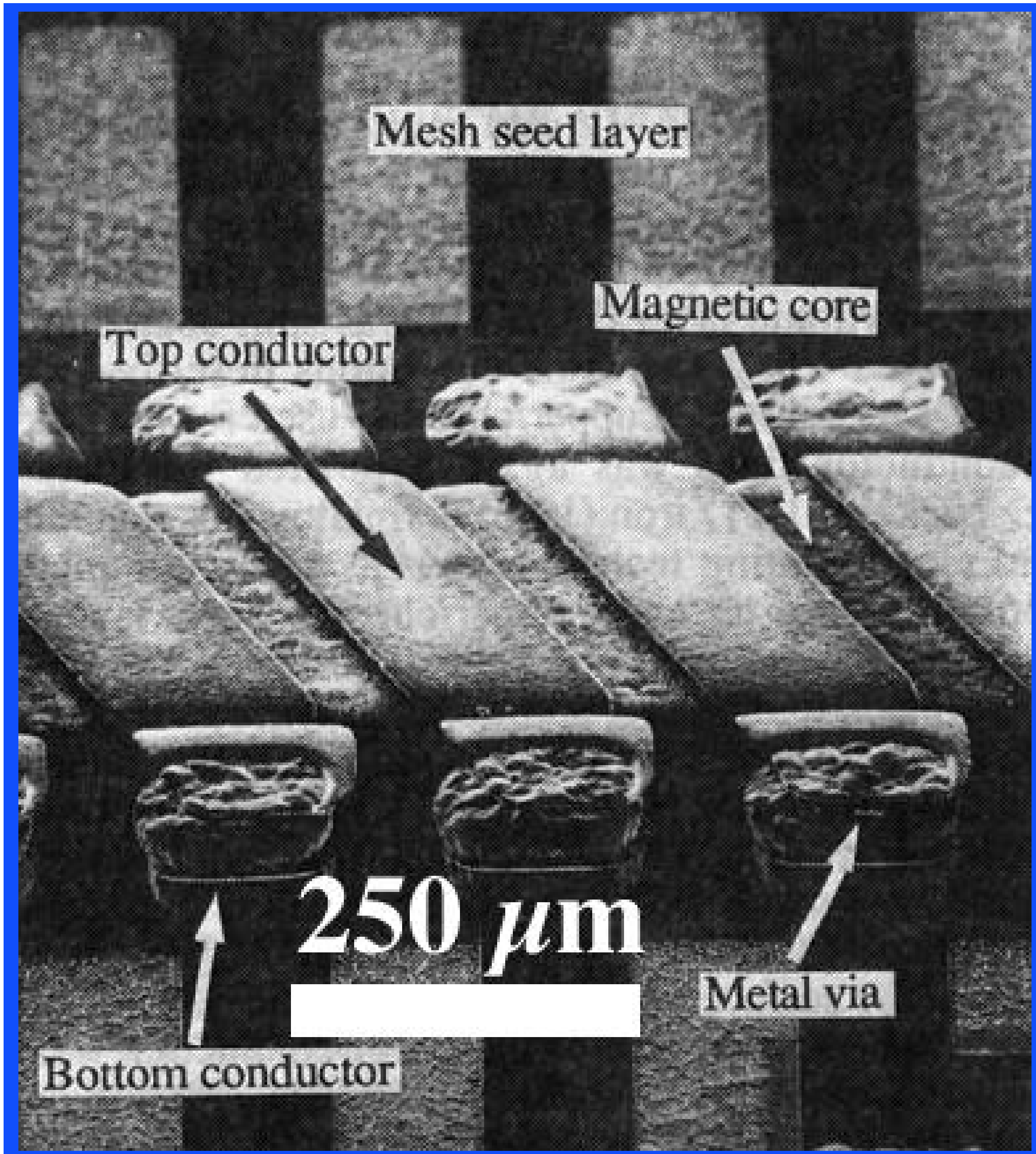
Reference: Halliday, D., Resnick, R., and Walker, J., "Fundamentals of Physics," Fourth Edition, John Wiley and Sons, Inc., New York, NY, 1993.



ELECTROPLATED COILS

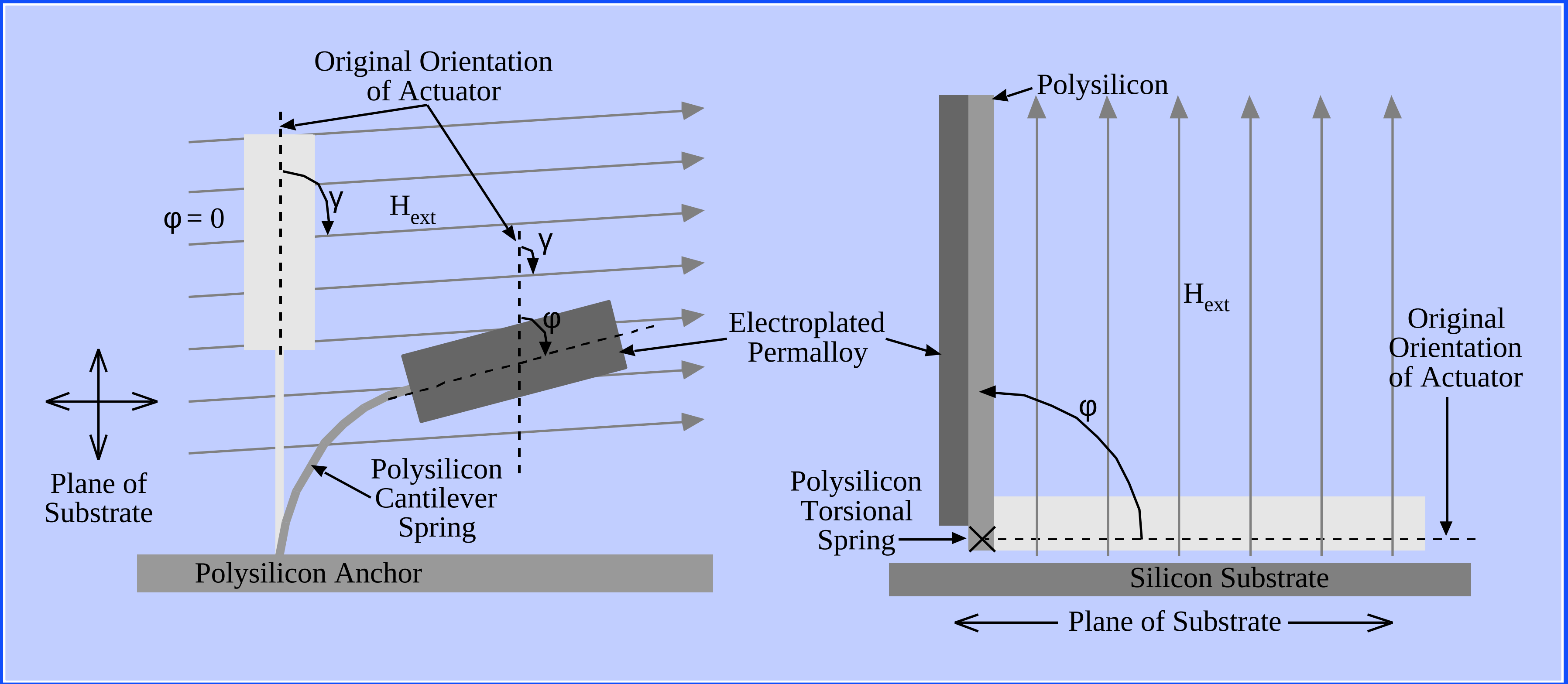


Reference: Ahn, C. H., and Allen, M. G., "A Fully Integrated Micromagnetic Actuator with a Multilevel Meander Magnetic Core," Technical Digest of the 1992 Solid-State Sensor and Actuator Workshop, Hilton Head Island, SC, June 22 - 25, 1992, pp. 14 - 18.



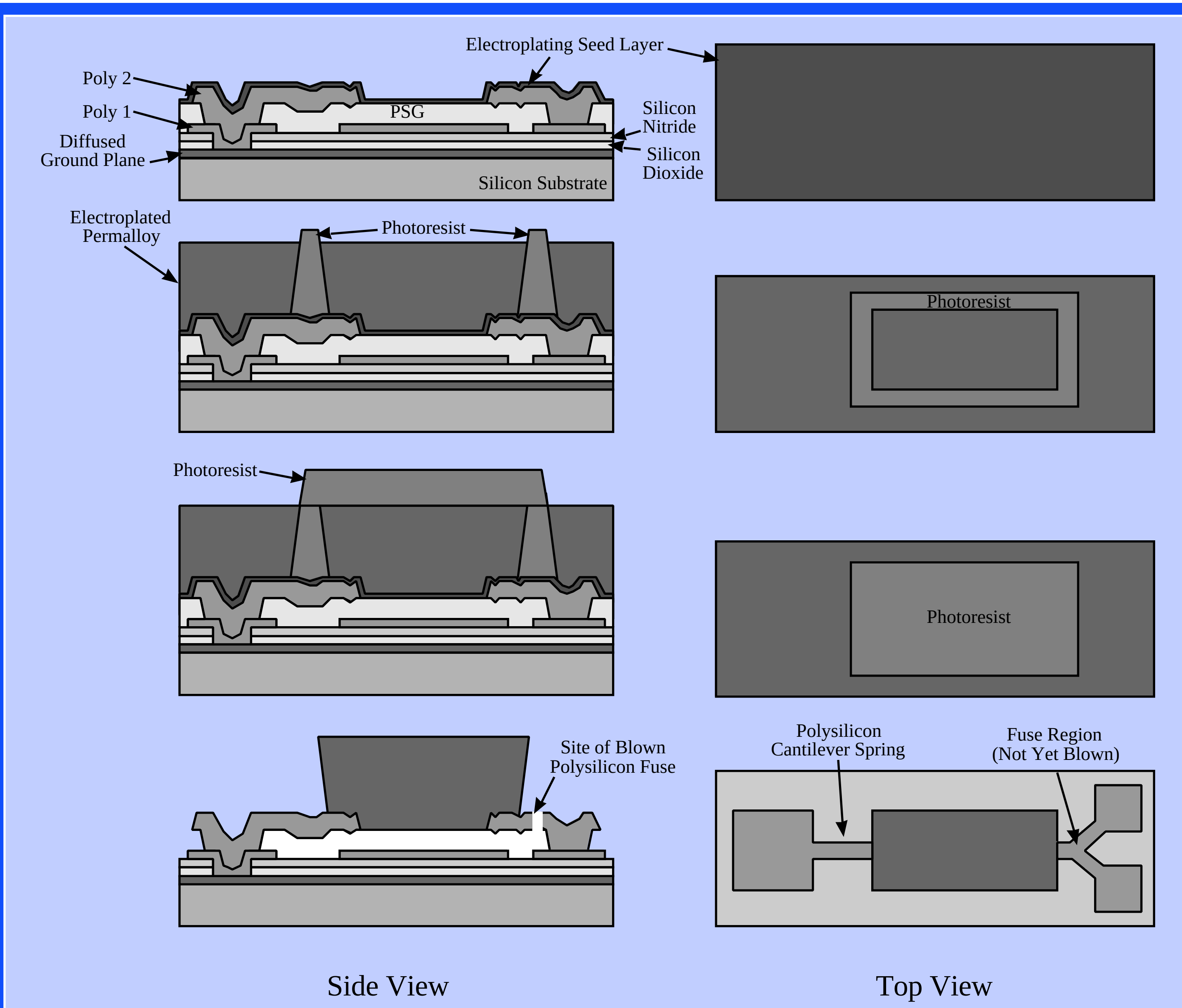
Source: Ahn, C. H., Kim, Y. J., and Allen, M. G., “A Fully-Integrated Micromachined Toroidal Inductor with a Nickel-Iron Magnetic Core (The Switched DC/DC Boost Converter Application),” Proceedings of Transducers ‘93, the 7th International Conference on Solid-State Sensors and Actuators, Yokohama, Japan, June 7 - 10, 1993, Institute of Electrical Engineers, Japan, pp. 70 - 73.

ACTUATORS USING EXTERNAL FIELDS

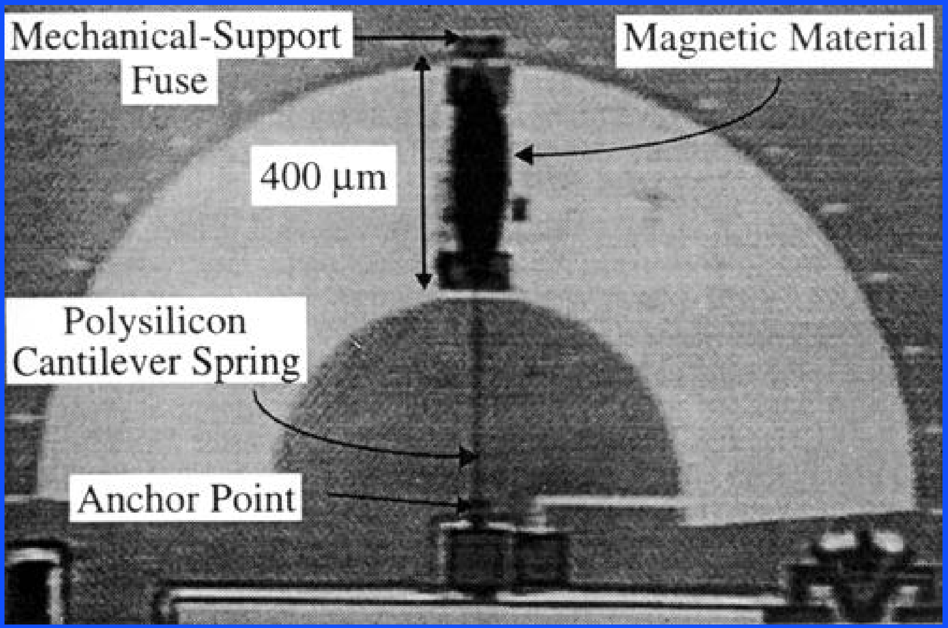


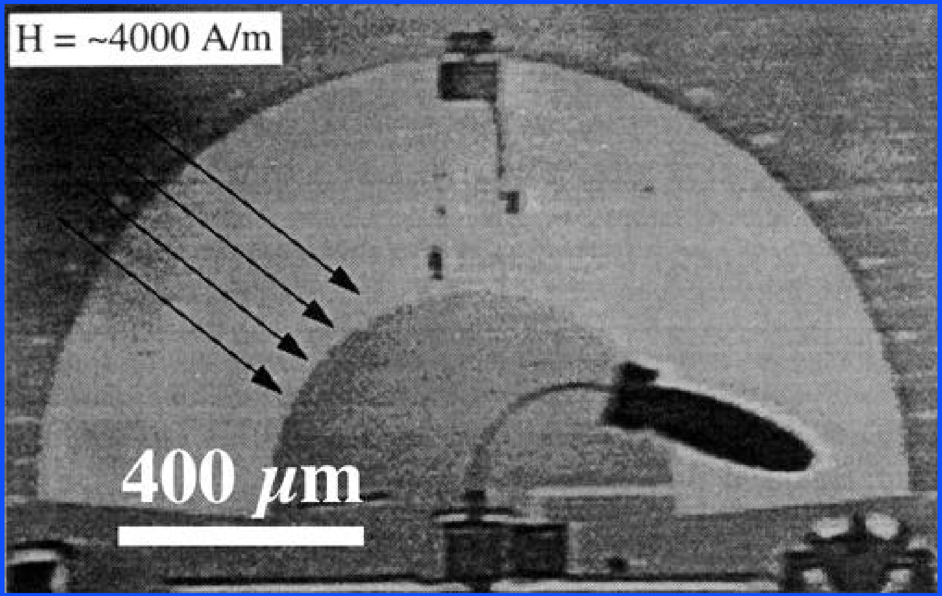
References: Judy, J. W., Muller, R. S., and Zappe, H. H., "Magnetic Microactuation of Polysilicon Flexure Structures," Technical Digest of the 1994 Solid-State Sensor and Actuator Workshop, Hilton Head Island, SC, June 13 -16, 1994, pp. 43 - 48.

Judy, J., and Muller, R. S., "Magnetic Microactuation of Torsional Polysilicon Structures," Digest of Technical Papers, Transducers 95, Stockholm, Sweden, June 25 - 29, 1995, vol. 1, pp. 332 - 335.



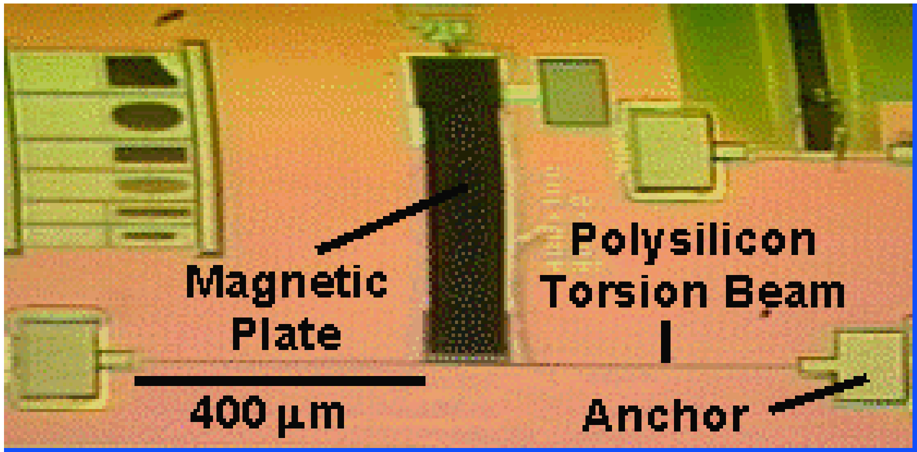
Reference: Judy, J. W., Muller, R. S., and Zappe, H. H., "Magnetic Microactuation of Polysilicon Flexure Structures," Technical Digest of the 1994 Solid-State Sensor and Actuator Workshop, Hilton Head Island, SC, June 13 -16, 1994, pp. 43 - 48.

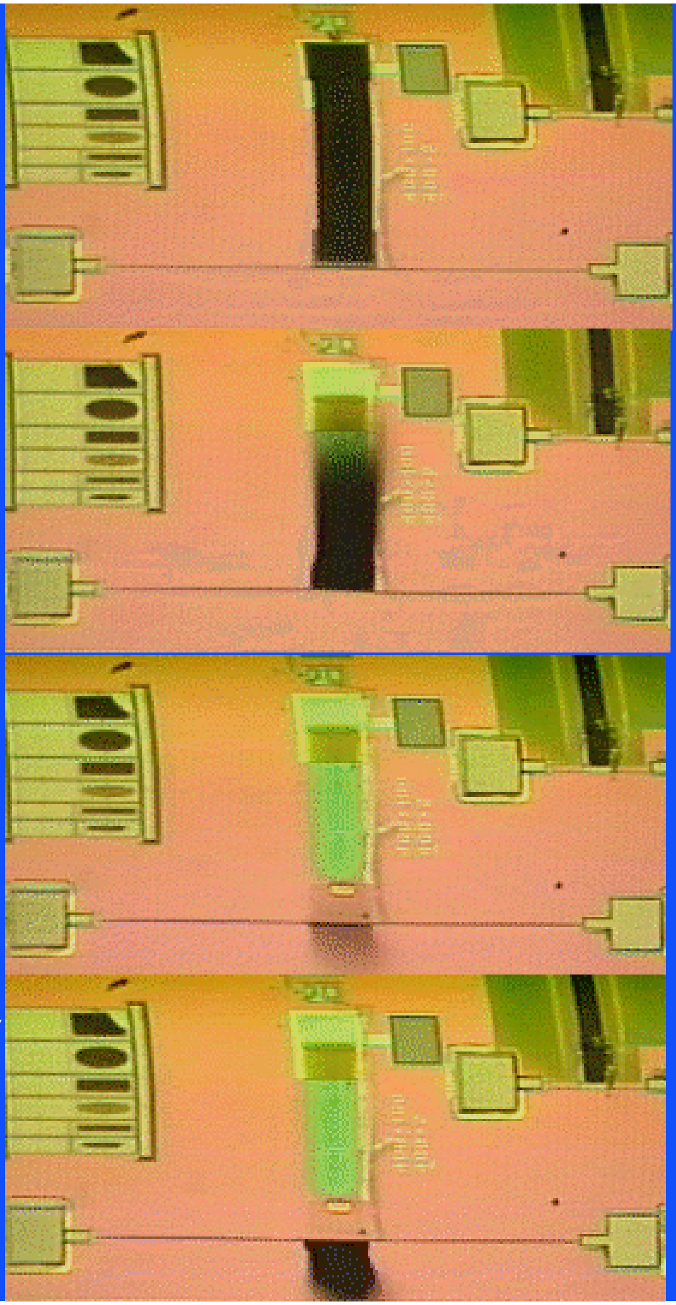




Reference: Judy, J. W., Muller, R. S., and Zappe, H. H., "Magnetic Microactuation of Polysilicon Flexure Structures," Technical Digest of the 1994 Solid-State Sensor and Actuator Workshop, Hilton Head Island, SC, June 13 -16, 1994, pp. 43 - 48.

Courtesy Prof. J. Judy, U.C.L.A.

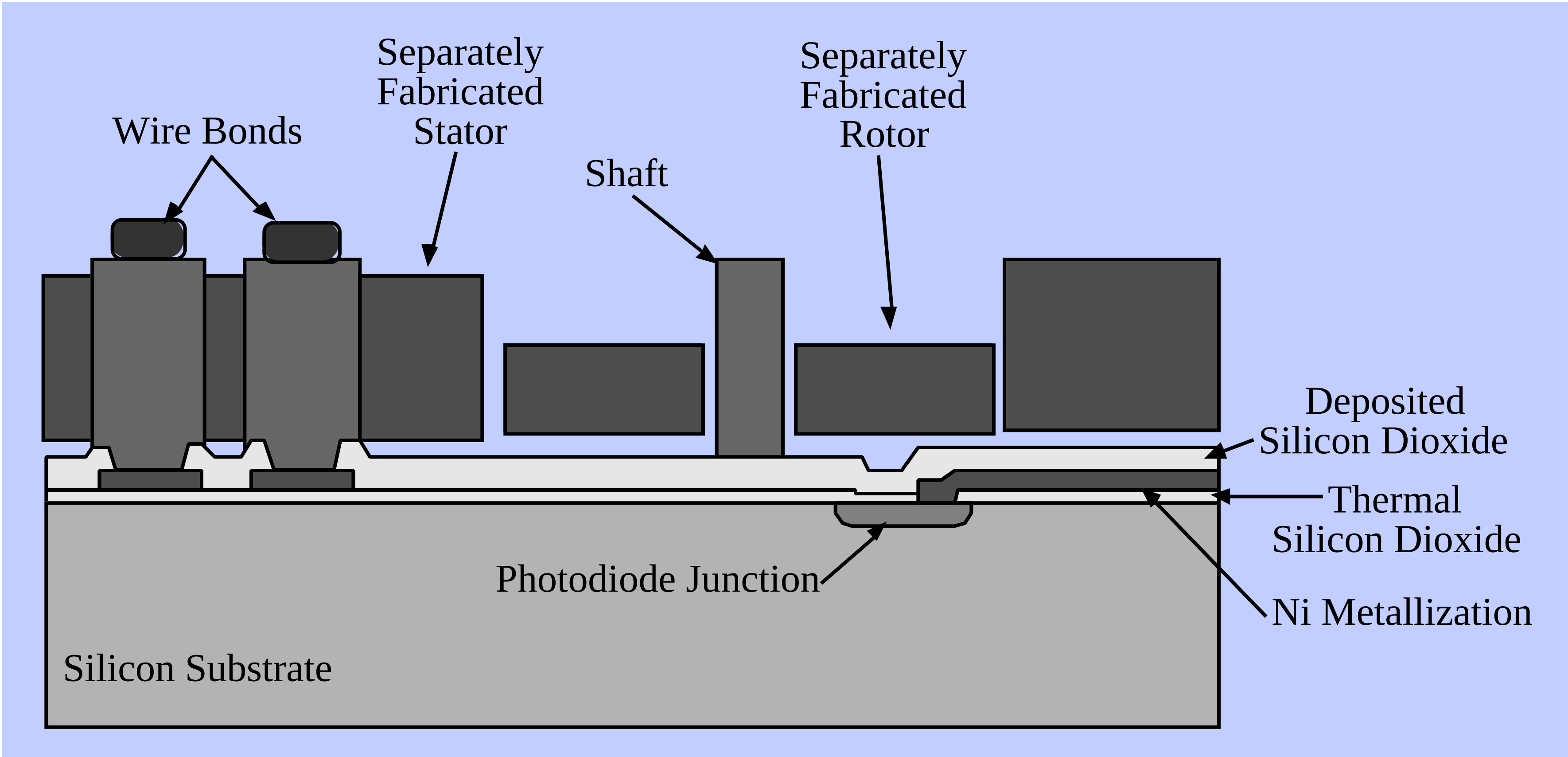




INCREASING FIELD STRENGTH, H

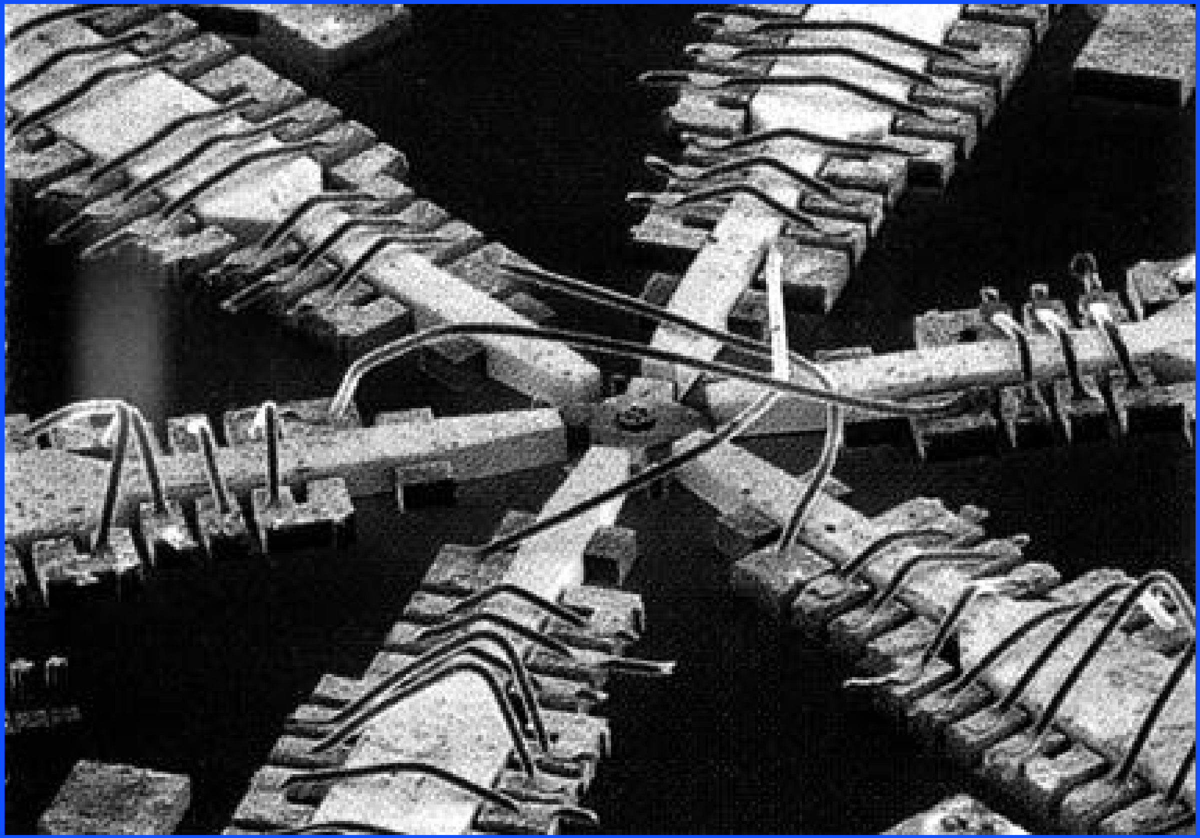
Courtesy Prof. J. Judy, U.C.L.A.

MAGNETIC MICROMOTORS



Reference: Guckel, H., Christenson, T. R., Skrobis, K. J., Jung, T. S., Klein, J., Hartojo, K. V., and Widjaja, I., "A First Functional Current Excited PLanar Rotational Magnetic Micromotor," Proceedings of the IEEE Micro Electro Mechanical Systems Conference, MEMS '93, Fort Lauderdale, FL, Feb. 1993, pp. 7 - 11.

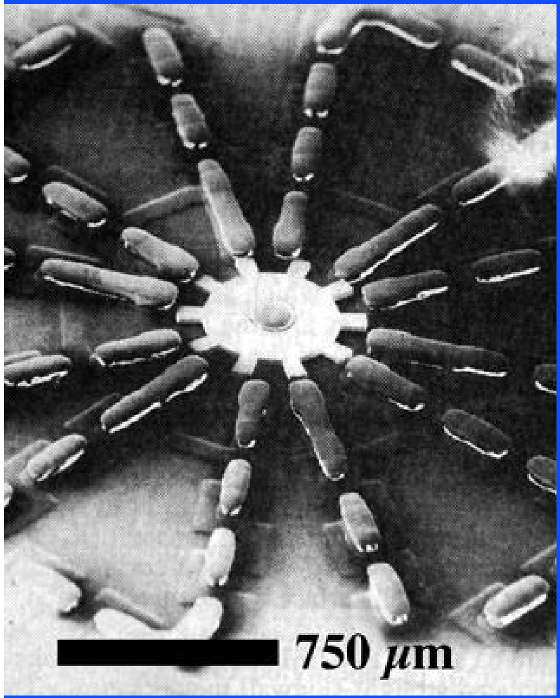
MAGNETIC MOTOR

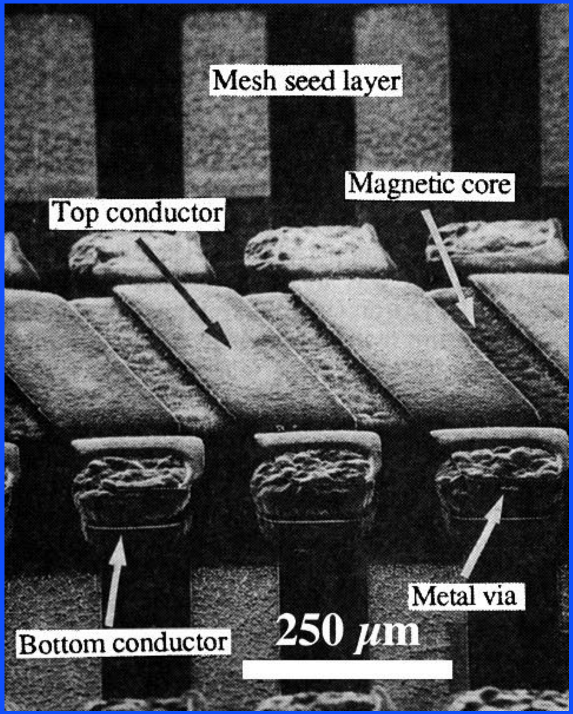


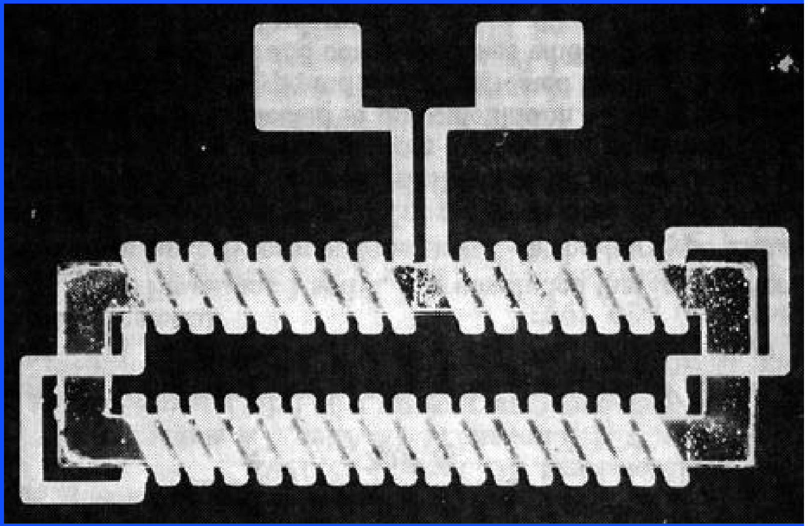
Courtesy Prof. H. Guckel, University of Wisconsin. See Mechanical Transducers Section for more information regarding magnetic micromotors.

Reference: Guckel, H., Christenson, T. R., Skrobis, K. J., Jung, T. S., Klein, J., Hartojo, K. V., and Widjaja, I., "A First Functional Current Excited PLanar Rotational Magnetic Micromotor," Proceedings of the IEEE Micro Electro Mechanical Systems Conference, MEMS '93, Fort Lauderdale, FL, Feb. 1993, pp. 7 - 11.

ELECTROPLATED COILS

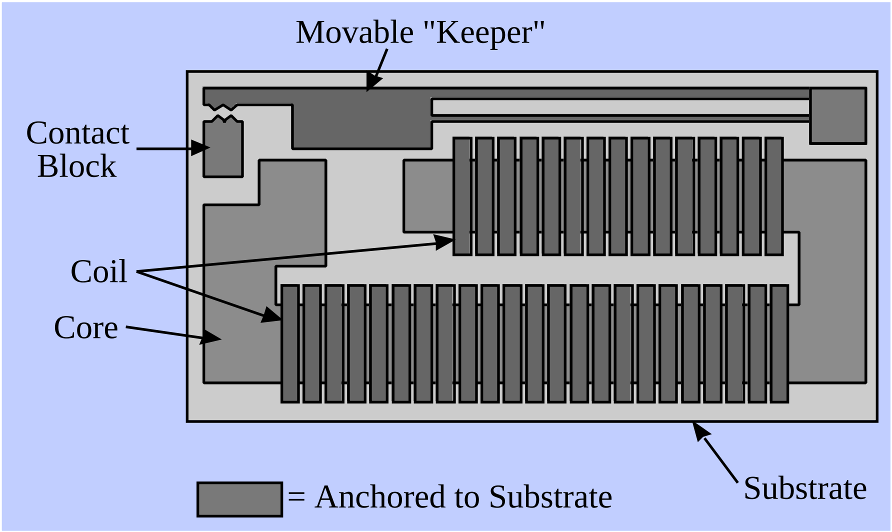


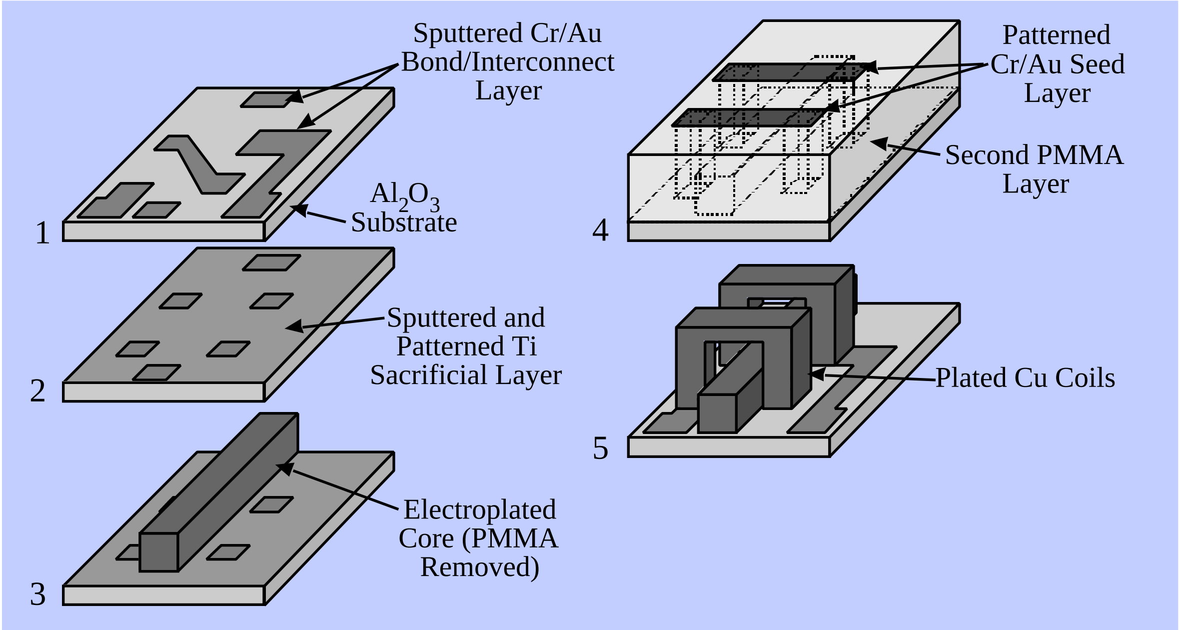




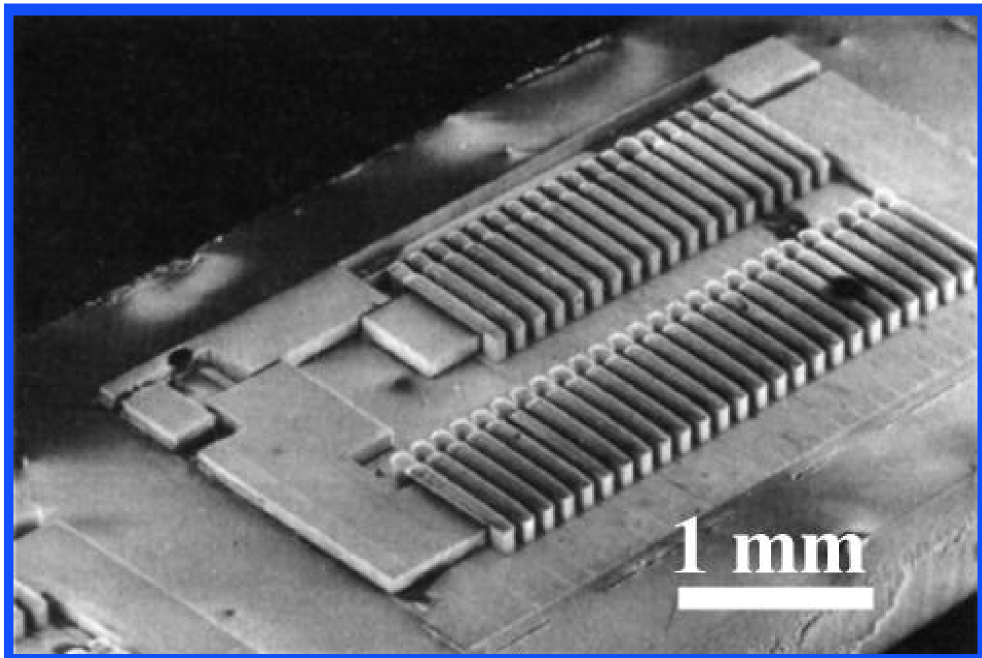
Source: Ahn, C. H., Kim, Y. J., and Allen, M. G., "A Fully-Integrated Micromachined Toroidal Inductor with a Nickel-Iron Magnetic Core (The Switched DC/DC Boost Converter Application)," Proceedings of Transducers '93, the 7th International Conference on Solid-State Sensors and Actuators, Yokohama, Japan, June 7 - 10, 1993, Institute of Electrical Engineers, Japan, pp. 70 - 73.

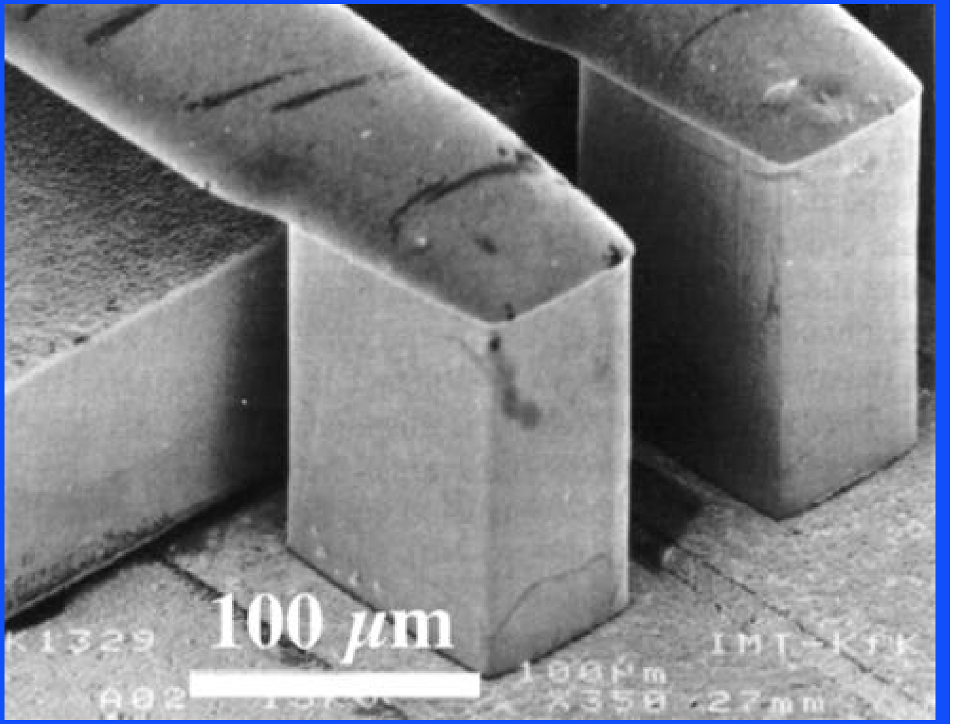
MAGNETIC MICRORELAYS





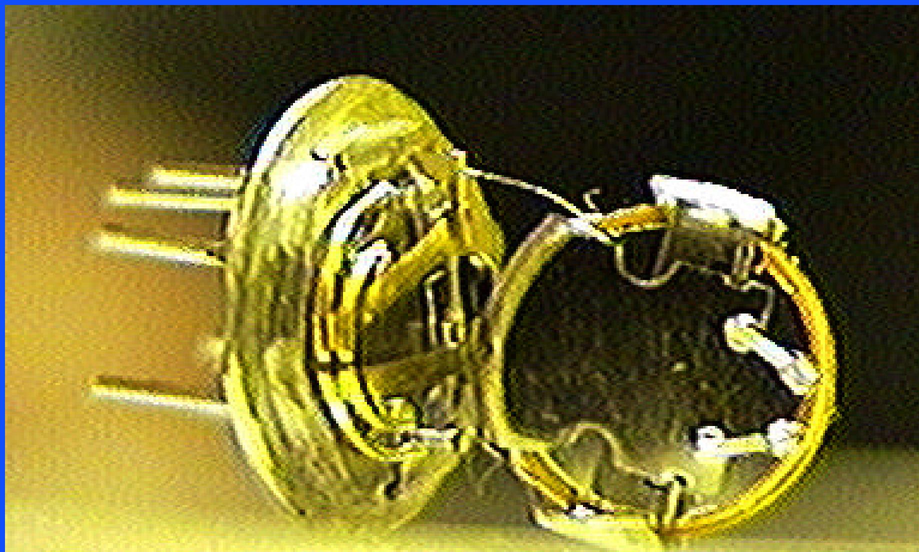
Reference: Rogge, B., Schulz, J., Mohr, J., Thommes, A., and Menz, W., "Fully Batch Fabricated Magnetic Microactuators Using a Two Layer LIGA Process," Digest of Technical Papers, Transducers 95, Stockholm, Sweden, June 25 - 29, 1995, vol. 1, pp. 320 - 323.

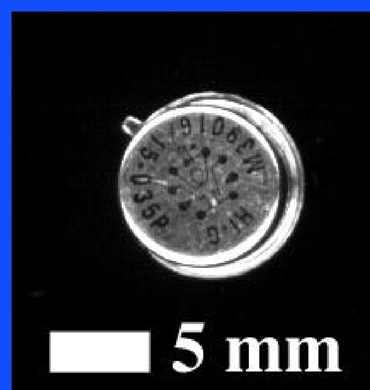




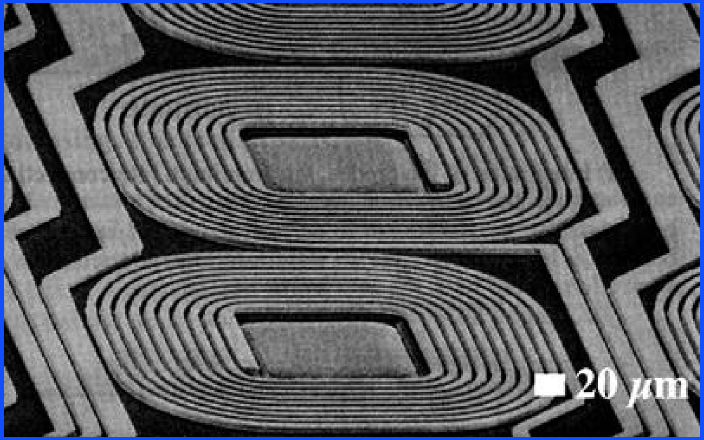
Source: Rogge, B., Schulz, J., Mohr, J., Thommes, A., and Menz, W., “Fully Batch Fabricated Magnetic Microactuators Using a Two Layer LIGA Process,” Digest of Technical Papers, Transducers 95, Stockholm, Sweden, June 25 - 29, 1995, vol. 1, pp. 320 - 323.

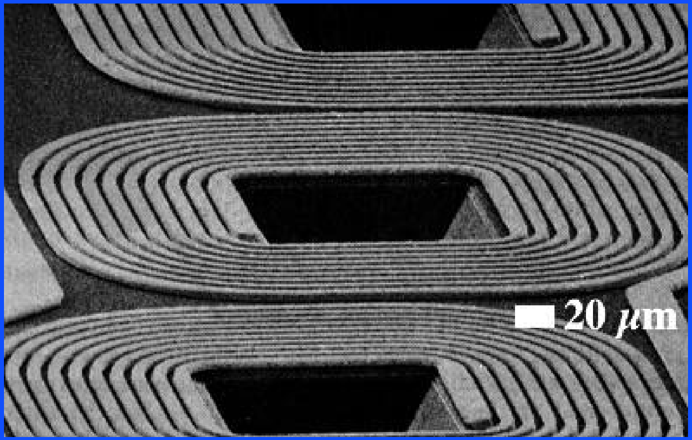
CONVENTIONAL MICRORELAY

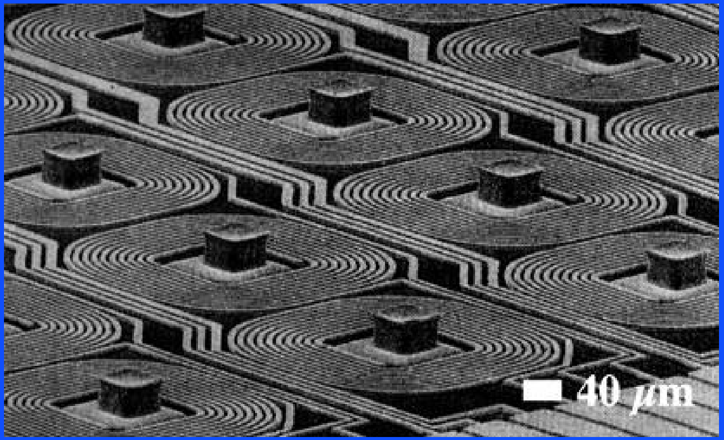




PLATED MAGNETIC PRINT HEADS





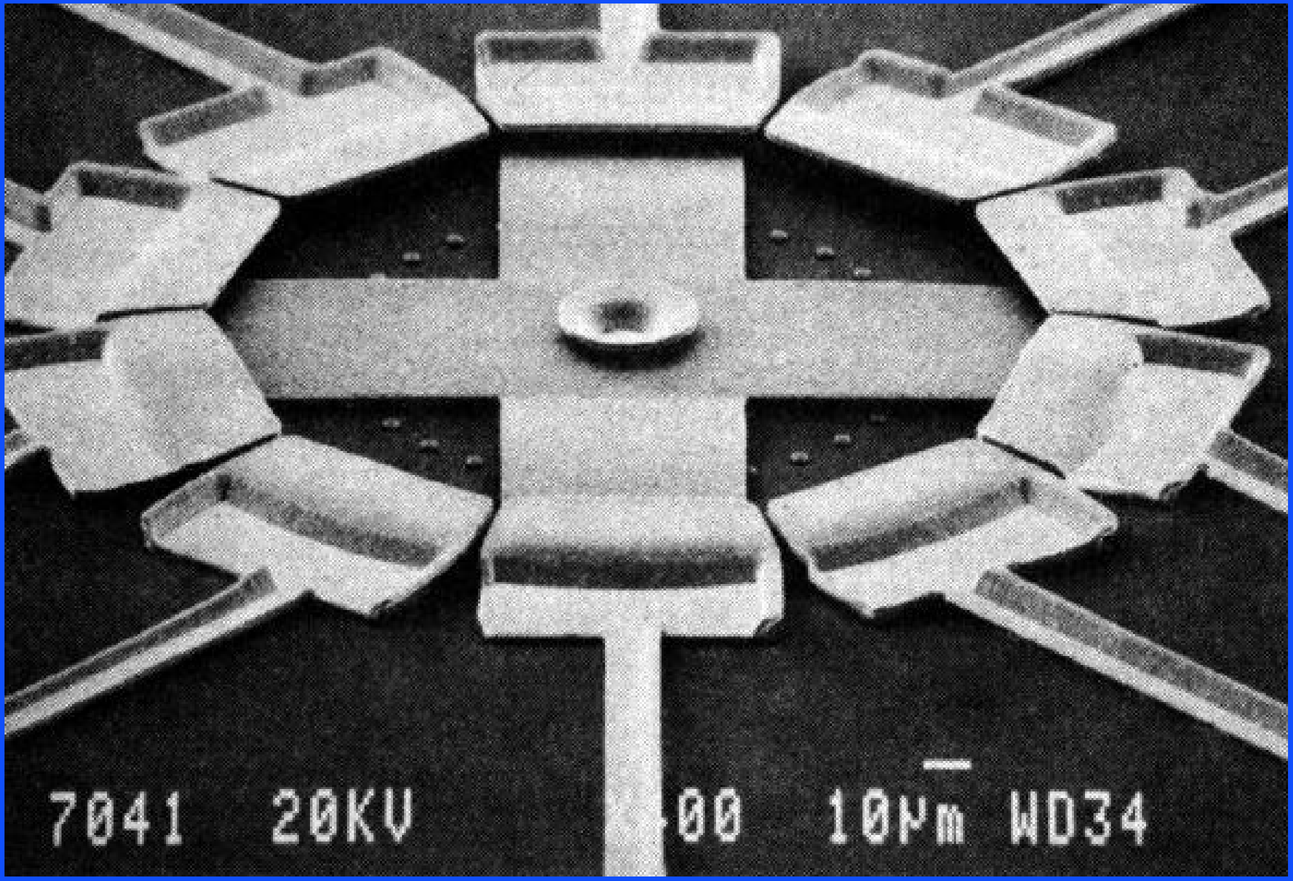


Source: Cardot, F., Gobet, J., Bogdanski, M., and Rudolf, F., "Microfabrication of High-Density Arrays of Microelectromagnets with On-Chip Electronics," Proceedings of Transducers '93, the 7th International Conference on Solid-State Sensors and Actuators, Yokohama, Japan, June 7 - 10, 1993, Institute of Electrical Engineers, Japan, pp. 32 - 35.

RF APPLICATIONS

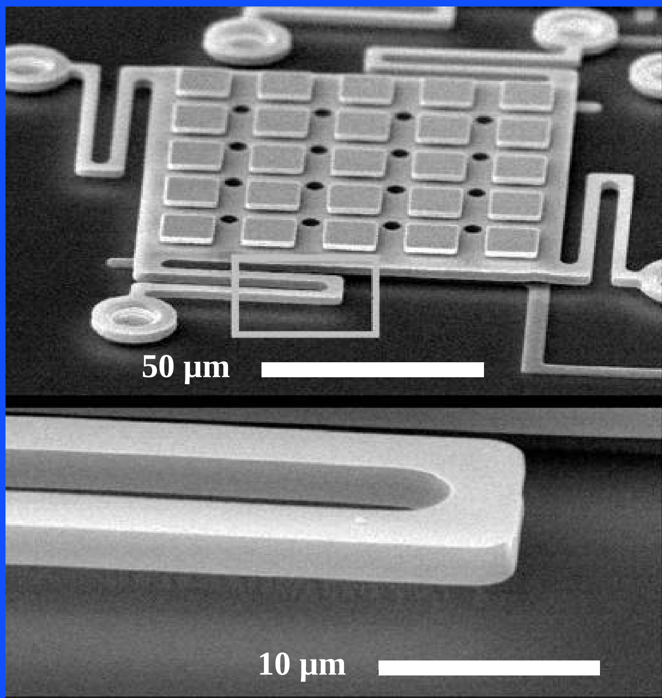
- As frequencies go higher in consumer telecommunications equipment and as cost pressures increase, micromachined RF components are becoming an important research area.
- Potential applications include RF switching, resonators/filters, oscillators, impedance matching, phase shifters, variable capacitors, etc.

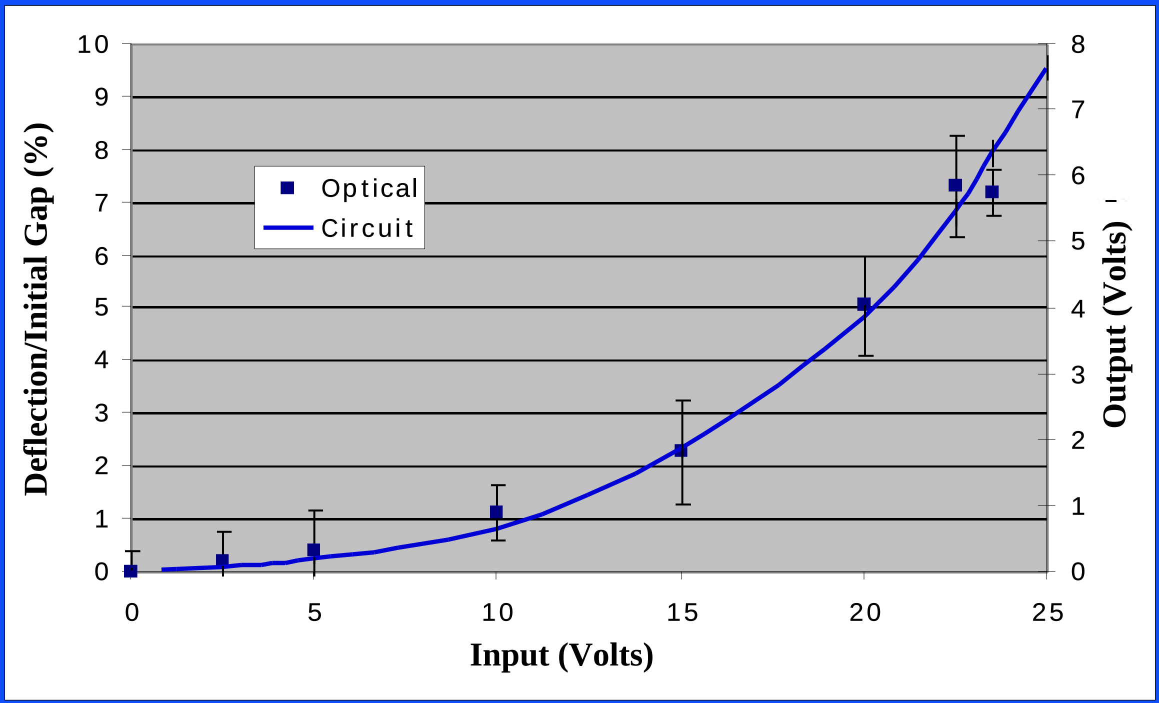
ROTARY RF SWITCH



Source: Hackett, R. H., Larson, L. E., and Melendes, M. A., "The Integration of Micro-Machine Fabrication with Electronic Device Fabrication on III-V Semiconductor Materials," Proceedings of Transducers '91, the 1991 International Conference on Solid-State Sensors and Actuators, San Francicso, CA, June 24 - 27, 1991, pp. 51 - 54.

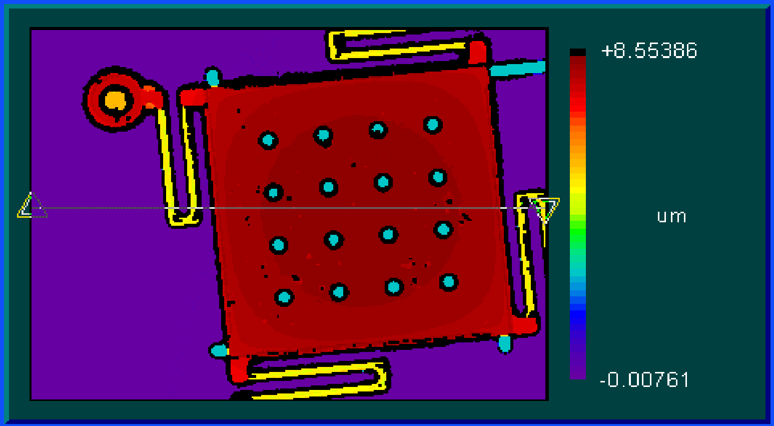
VARIABLE CAPACITOR WITH INTEGRATED CIRCUITRY

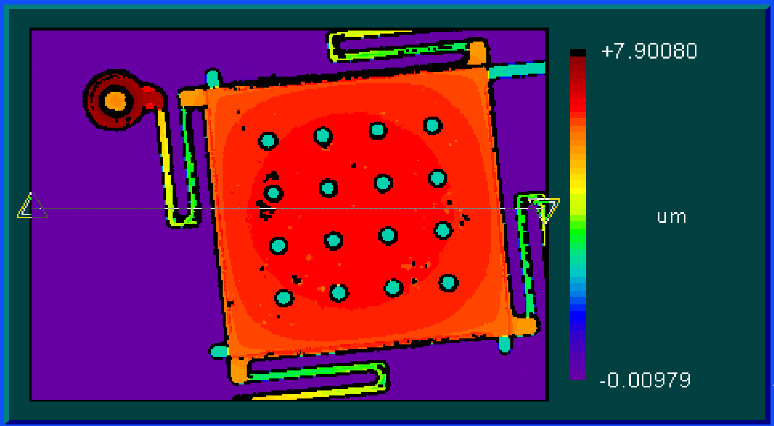




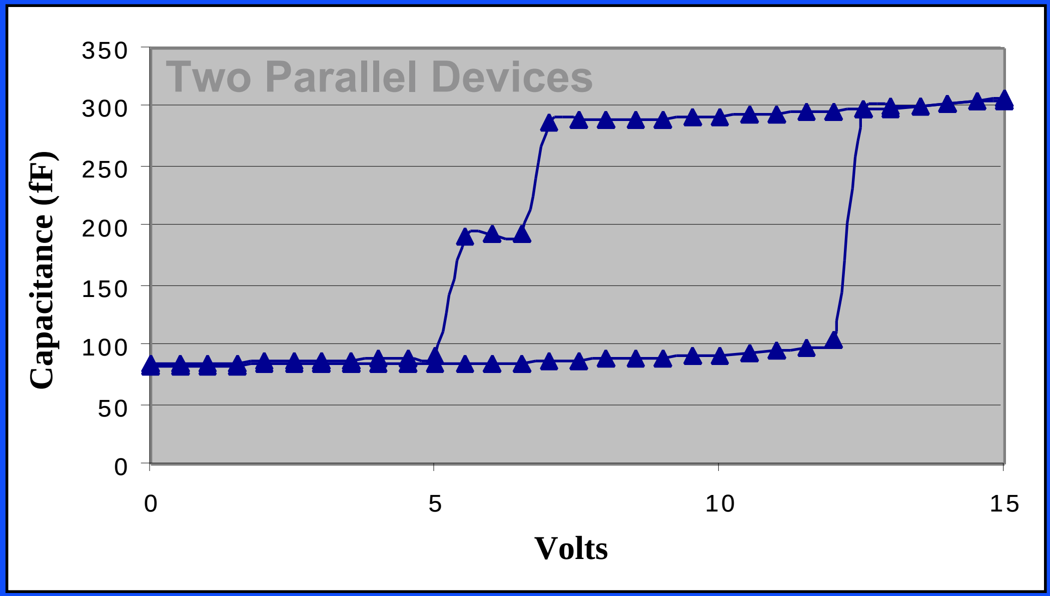
Courtesy K. Honer, Stanford University.

PROTOTYPE CAPACITIVE SWITCH





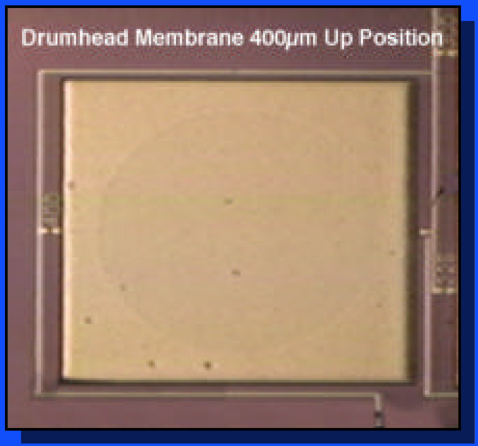
Up

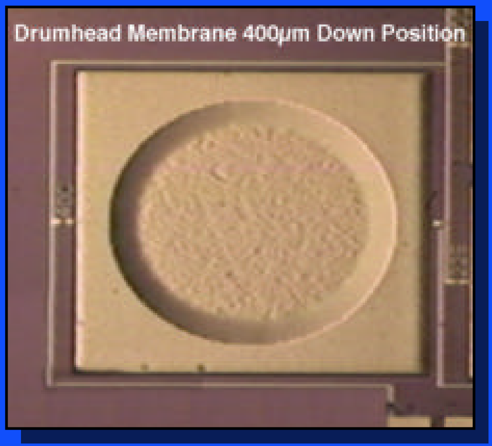


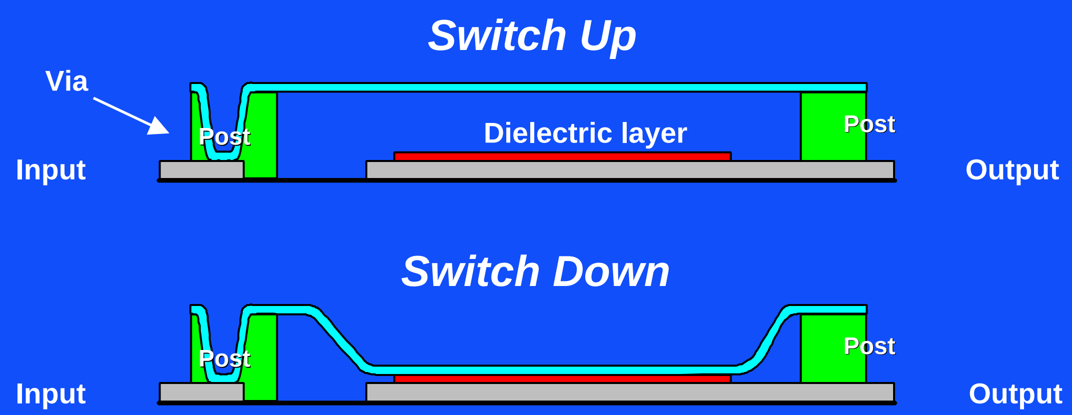
Down

Courtesy K. Honer, Stanford University.

TI DRUMHEAD RF SWITCH





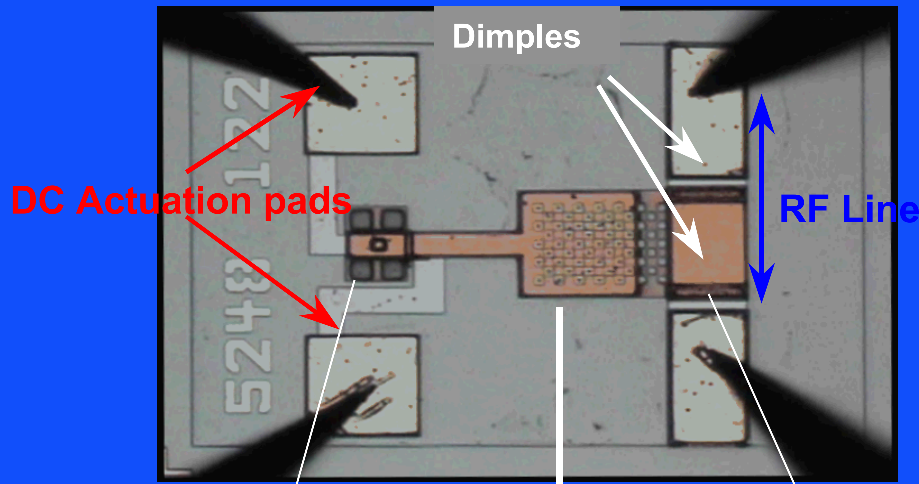


- Dielectric layer eliminates sticking of membrane and need for recessed electrodes
- Replaces resistive contact with capacitive contact
- Greater than 100:1 capacitance ratios available

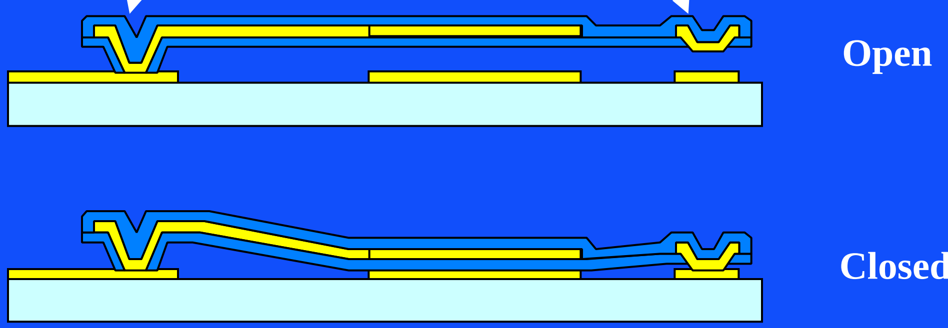
Courtesy Dr. C. Goldsmith, Texas Instruments, Inc.

HRL METAL CONTACT RF MEMS SWITCH

Top View



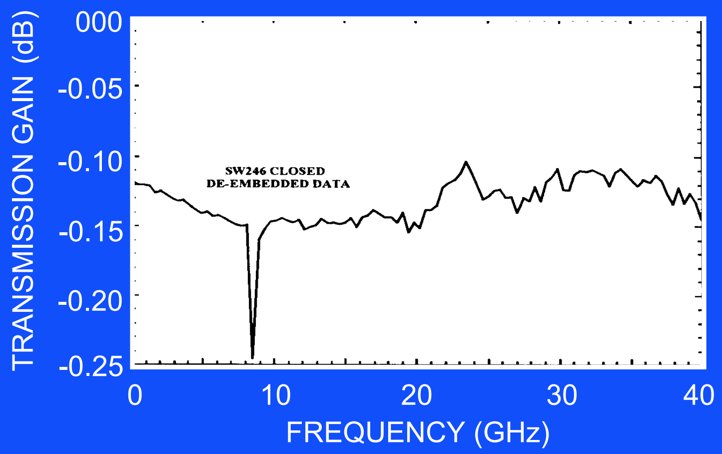
Side View

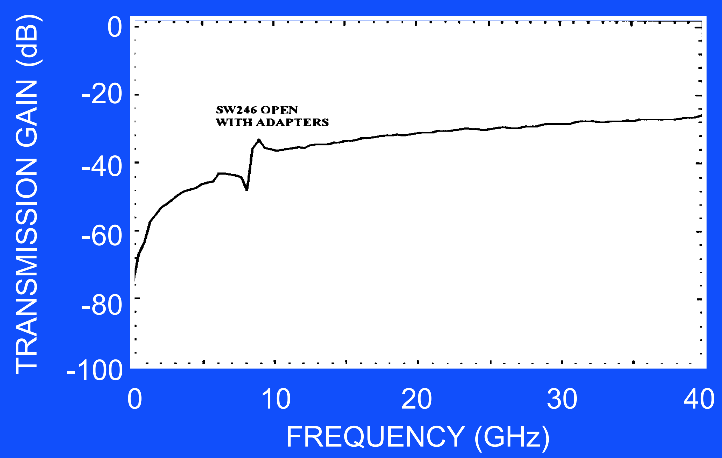


Courtesy Dr. R. Loo, HRL. Reference: "Surface-Micromachined RF MEMS Switches on GaAs substrates." International Journal of RF Microwave and Computer Aided Engineering, 9:348-361,1999, published by John Wiley & Sons, Inc.

HRL METAL CONTACT RF MEMS SWITCH

RF Performance



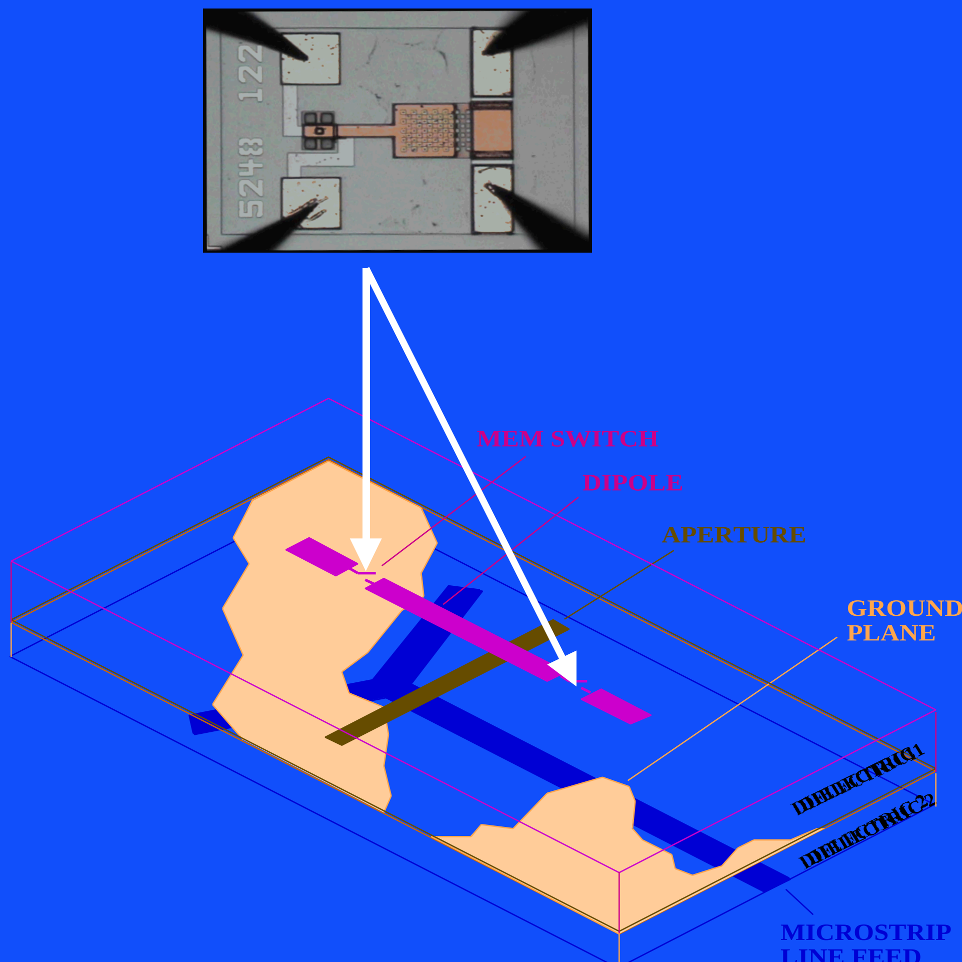


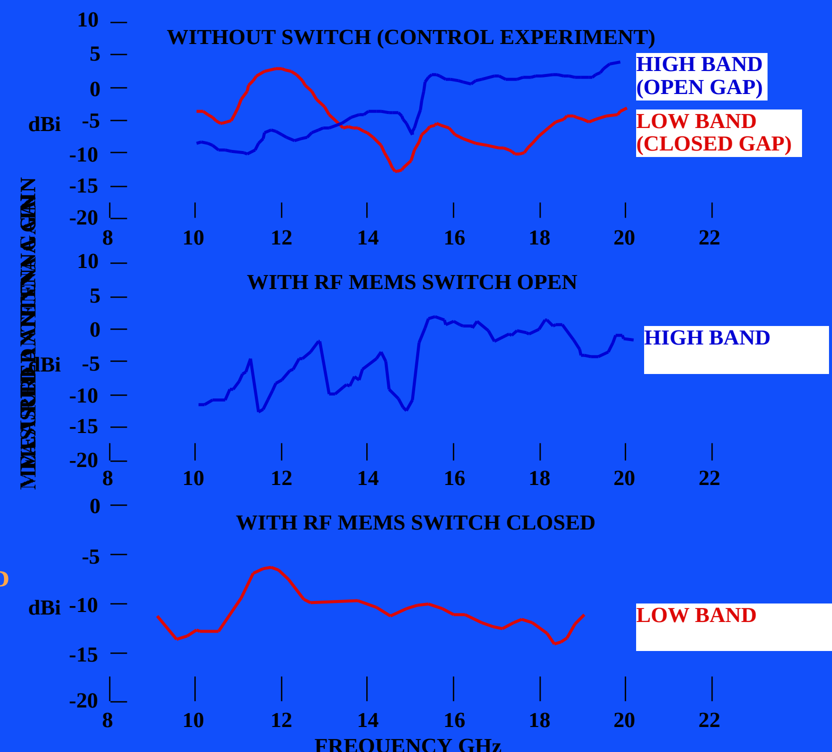
Mechanical Performance

Mean Actuation Voltage	30 V
Resonant Frequency	20 kHz
Response Time (0-90%)	40 μsec
Contact Force (per contact)	250-300 μN
Mean Total Resistance (bonded)	1.0 Ω
Mechanical Actuation Lifetime	10^9
Electrical Actuation Lifetime (1 kHz)	10^6

Courtesy Dr. R. Loo, HRL. Reference: "Surface-Micromachined RF MEMS Switches on GaAs substrates." International Journal of RF Microwave and Computer Aided Engineering, 9:348-361,1999, published by John Wiley & Sons, Inc.

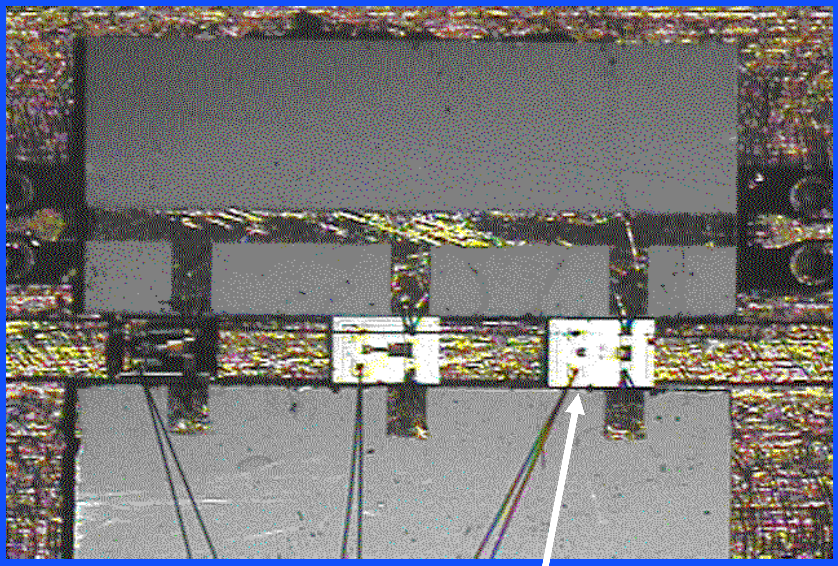
12 & 20 GHz DUAL FREQUENCY BAND, APERTURE FEED ANTENNA USING MEM SWITCHES

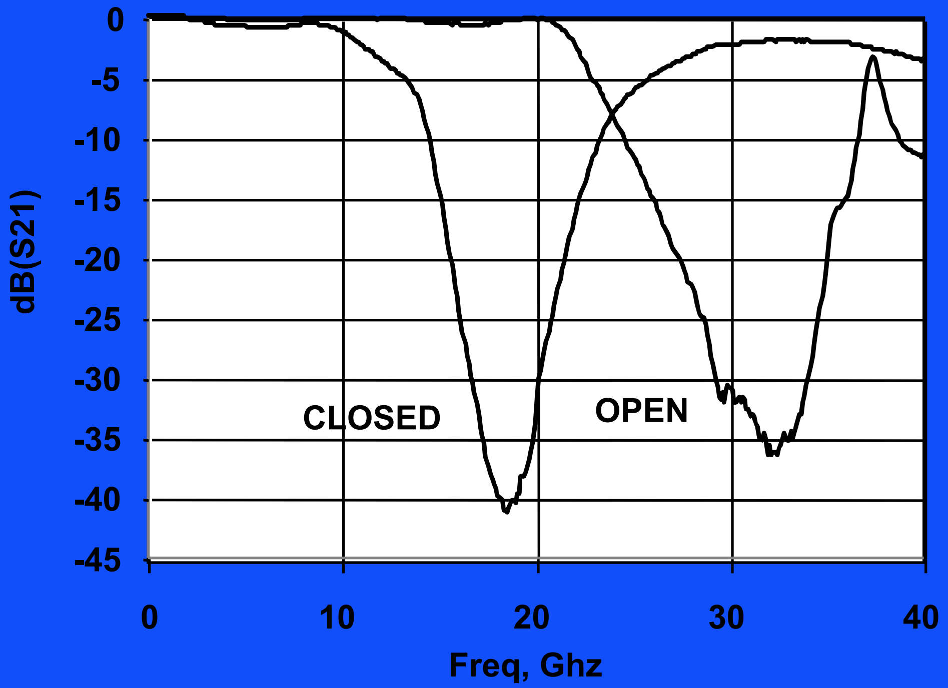




Courtesy Dr. R. Loo, HRL. Reference: "Surface-Micromachined RF MEMS Switches on GaAs substrates." International Journal of RF Microwave and Computer Aided Engineering, 9:348-361,1999, published by John Wiley & Sons, Inc.

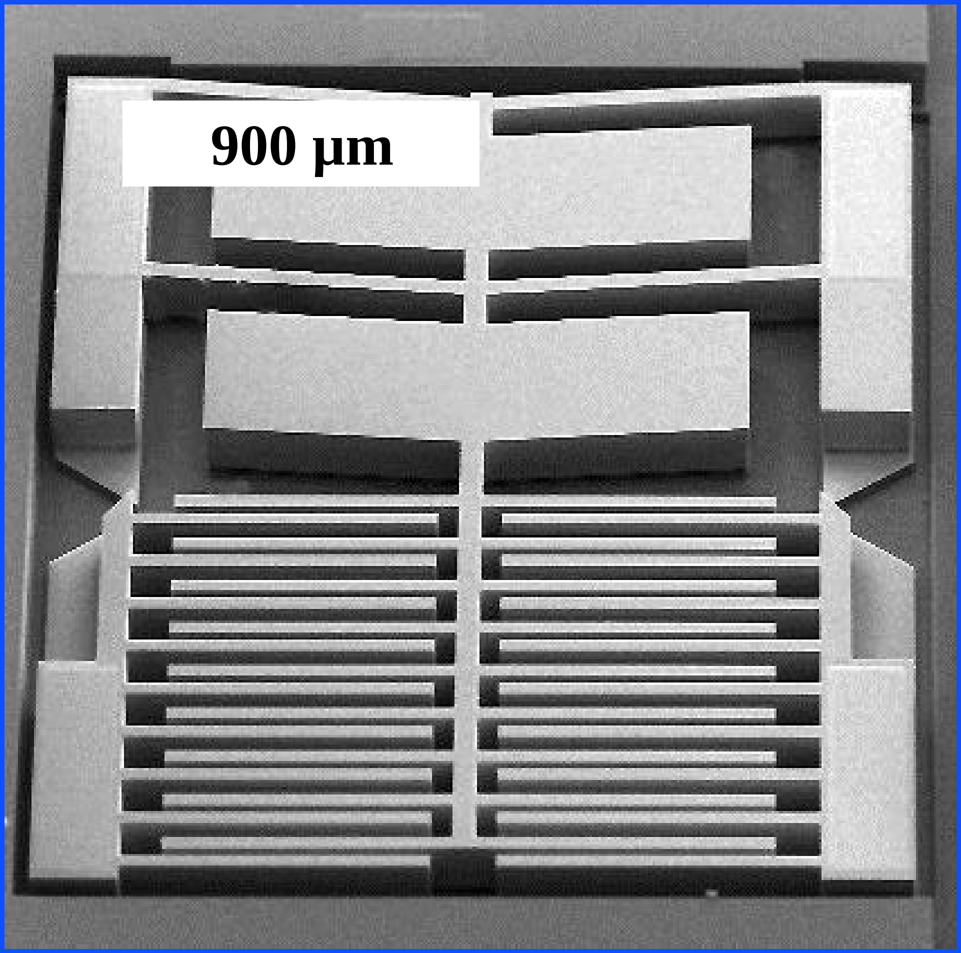
TUNABLE FILTER USING RF MEMS SWITCHES





Courtesy Dr. R. Loo, HRL. Reference: "Surface-Micromachined RF MEMS Switches on GaAs substrates." International Journal of RF Microwave and Computer Aided Engineering, 9:348-361,1999, published by John Wiley & Sons, Inc.

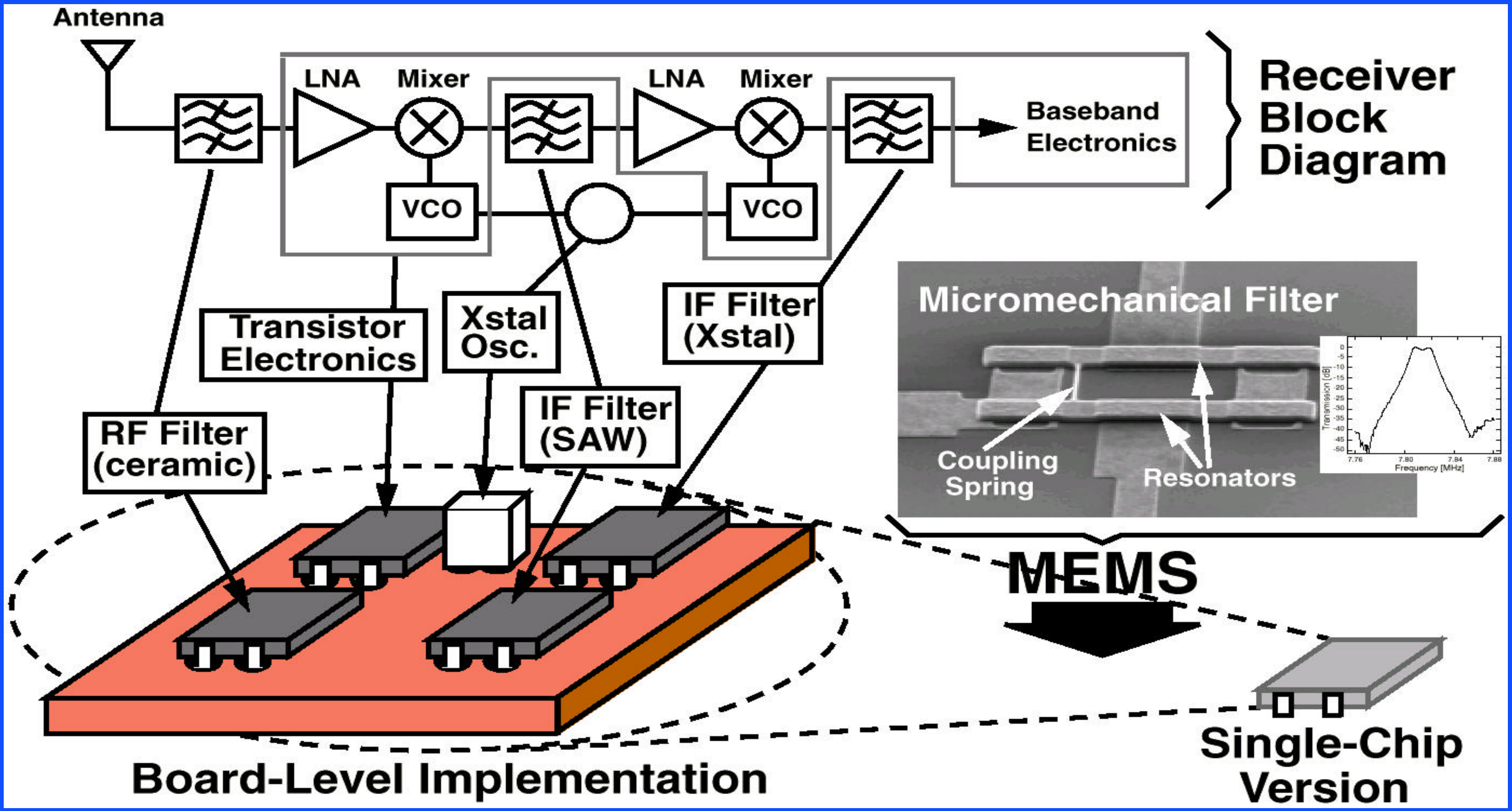
THERMALLY DRIVEN VARIABLE CAPACITOR



Courtesy Lucas NovaSensor.

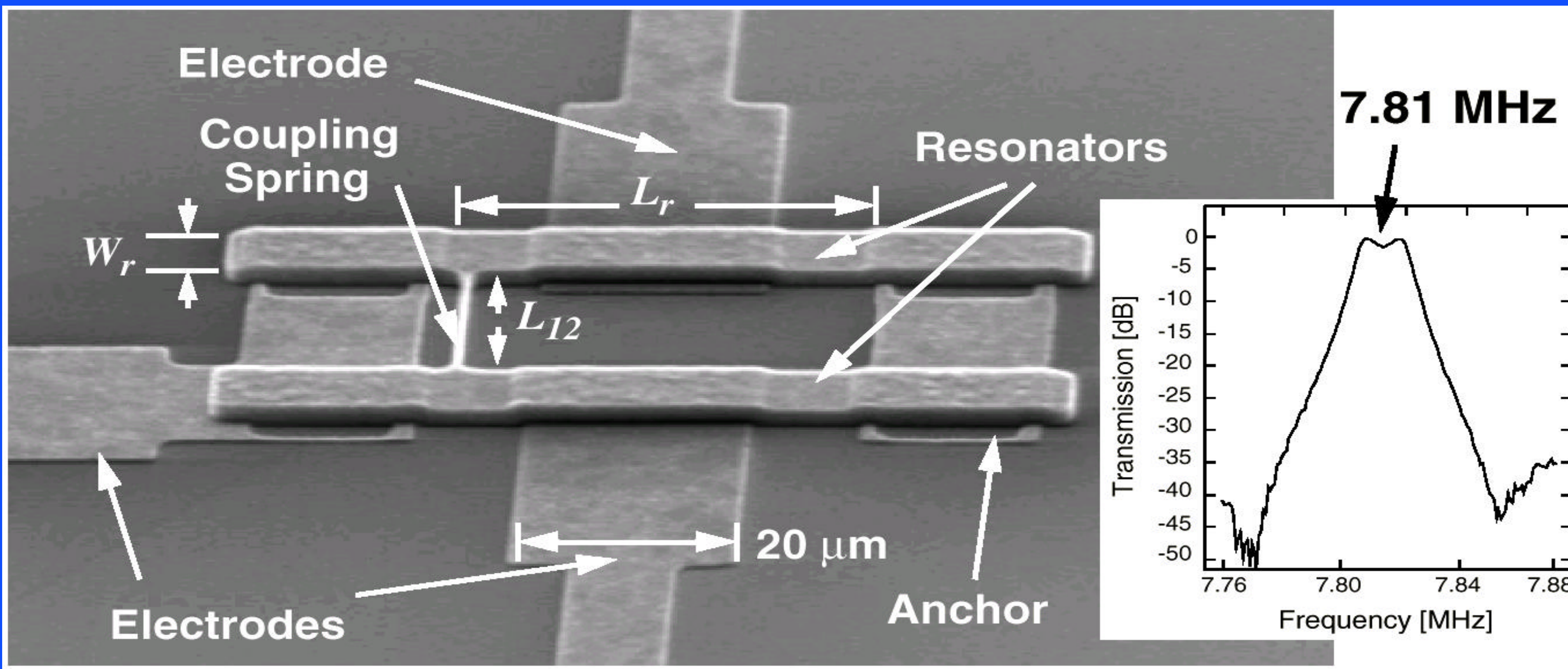
- 100 µm Tall
- 20 µm Wide Beams

RF MEMS RESONATORS



Courtesy Prof. C. Nguyen, University of Michigan.

HF SPRING-COUPLED MICROMECHANICAL FILTER



<u>2-Resonator HF</u>
(4th Order)
[Bannon, Clark, Nguyen 1996]

<u>Performance</u>

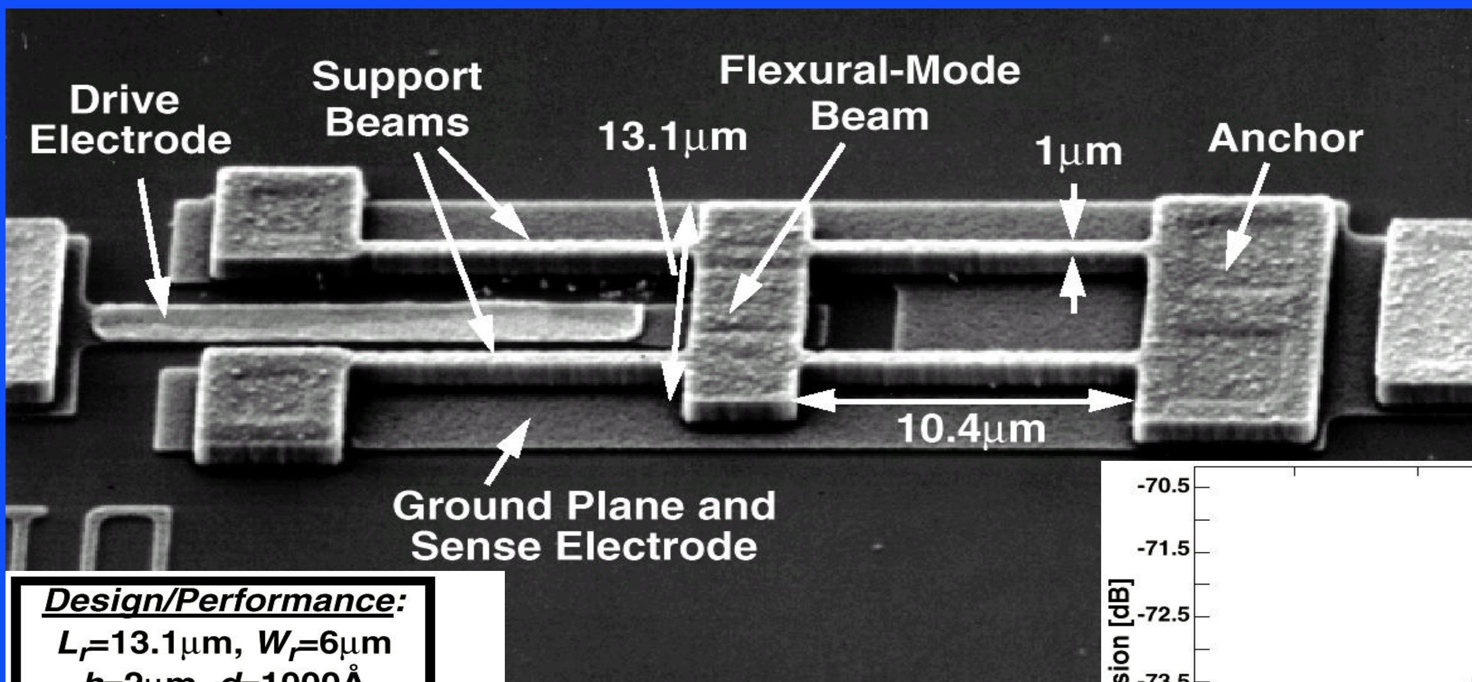
f_o=7.81MHz, BW=15kHz

Rej.=35dB, I.L.<2dB

Courtesy Prof. C. Nguyen, University of Michigan.

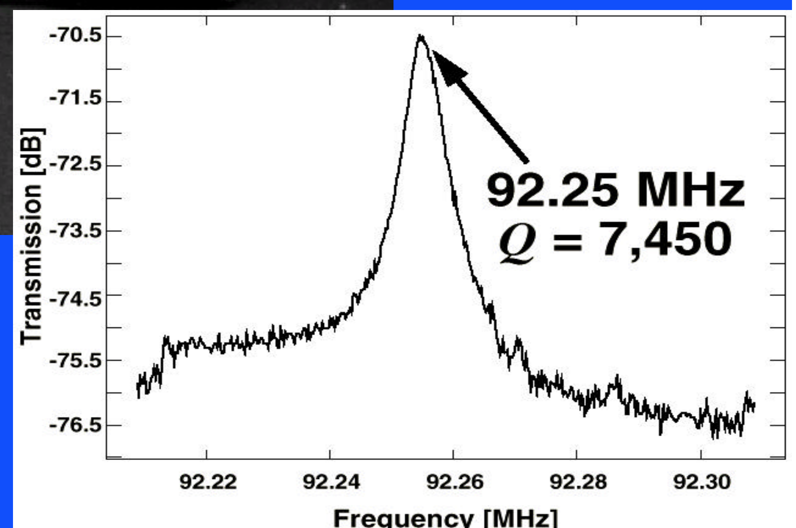
92 MHZ FREE-FREE BEAM μRESONATOR

- **Free-free beam μmechanical resonator with non-intrusive supports ➠ reduce anchor dissipation ➠ higher *Q***



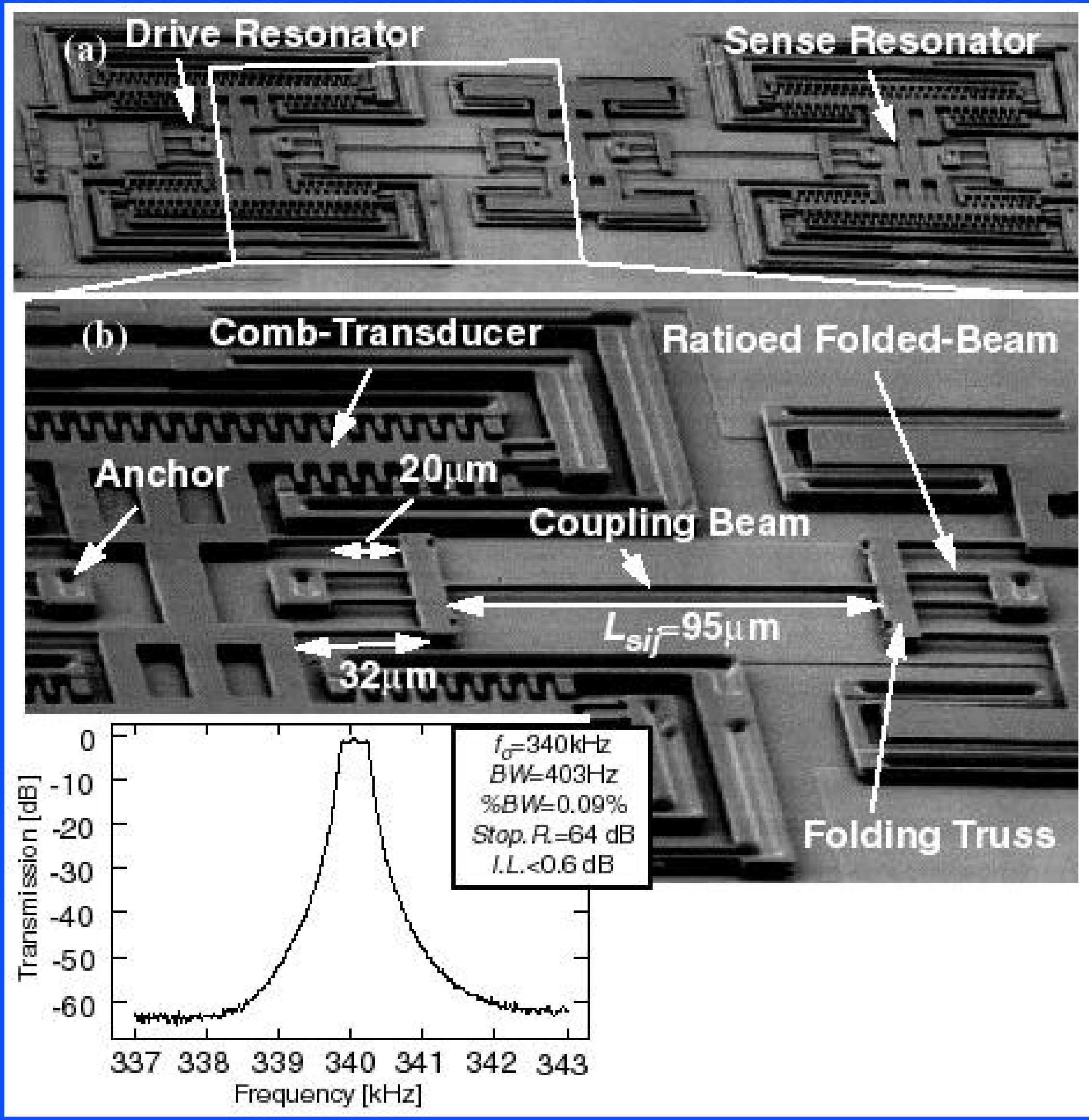
Design/Performance:
L_r=13.1μm, W_r=6μm
h=2μm, d=1000Å
V_P=28-76V, W_e=2.8μm
f_o~92.25MHz
Q~7,450 @ 10mTorr

[Wang, Yu, Nguyen 1998]



Reference: K. Wang, Y. Yu, A.-C. Wong, and C. T.-C. Nguyen, "VHF free-free beam high-Q micromechanical resonators," Technical Digest, 12th International IEEE Micro Electro Mechanical Systems Conference, Orlando, Florida, Jan. 17-21, 1999, pp. 453-458.

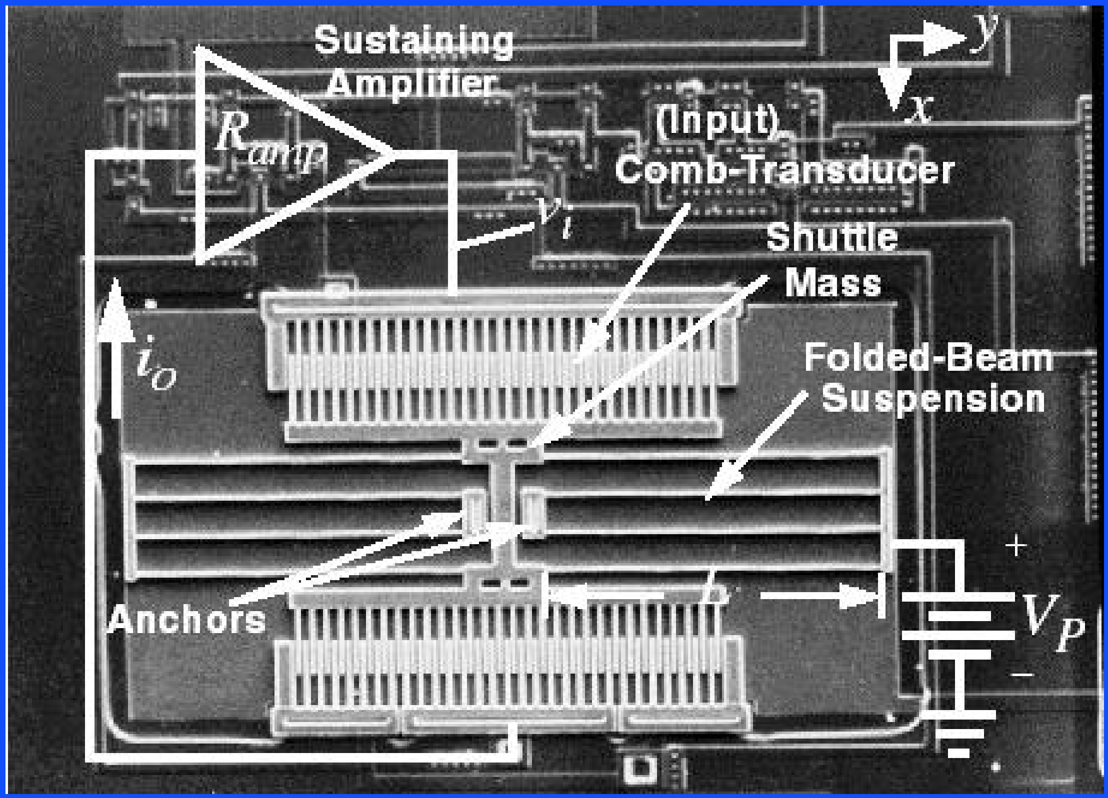
Courtesy Prof. C. Nguyen, University of Michigan.



Reference: K. Wang and C. T.-C. Nguyen, "High-order medium frequency micromechanical electronic filters," IEEE J. Microelectromech. Syst., vol. 8, no. 4, pp. 534-557, Dec. 1999.

Courtesy Prof. C. Nguyen, University of Michigan.

INTEGRATED CMOS RESONATOR/OSCILLATOR

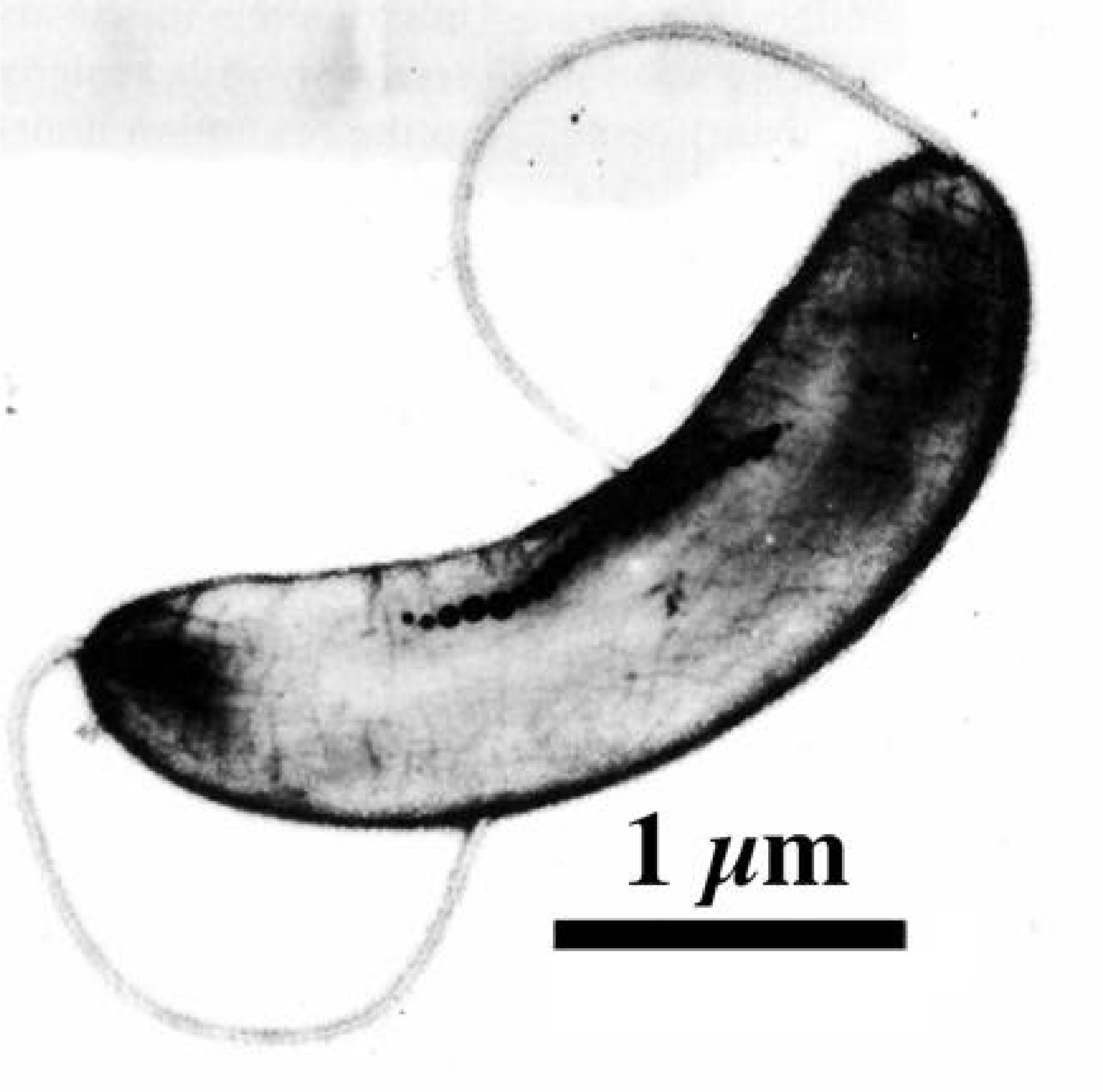


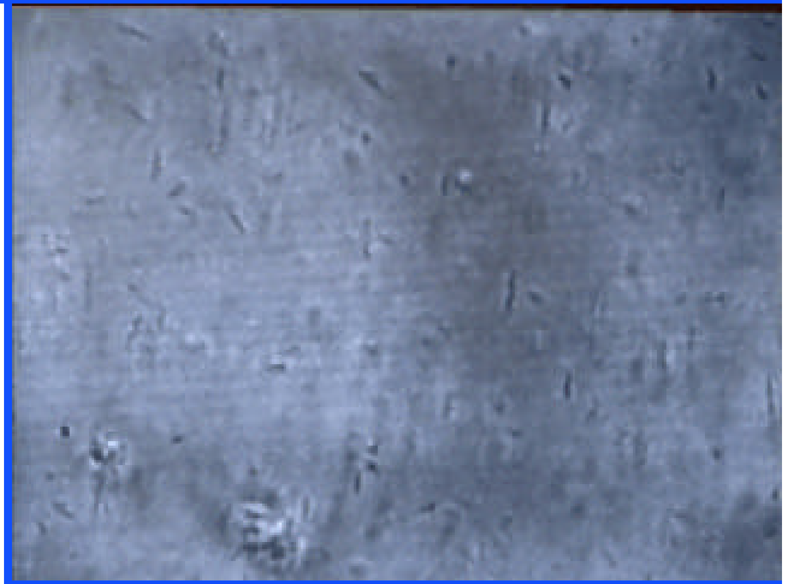
Reference: C. T.-C. Nguyen and R. T. Howe, "An integrated CMOS micromechanical resonator high-Q oscillator," IEEE J. Solid-State Circuits, vol. 34, no. 4, pp. 440-445, April 1999.

Courtesy Prof. C. Nguyen, University of Michigan.

BIOLOGICAL MAGNETIC TRANSDUCERS

- **In 1975, it was discovered by Blakemore and Frankel that certain bacteria (*Aquaspirillium magnetotacticum*) contained chains of ≈ 50 nm particles of permanently magnetized magnetite, synthesized by the bacteria themselves.**
- **The entire organism is passively rotated to orient to the Earth's magnetic field to help these anaerobic bacteria swim down (away from oxygen).**
- **Northern hemisphere bacteria swim toward north magnetic poles, and southern hemisphere bacteria move toward south poles.**
- **Magnetite has also been found in bees, sea turtles, trout, salmon and pigeons. Evidence to date suggests magnetic-to-neural transduction is taking place in these organisms.**





Movie courtesy Prof. H. C. Heller, Stanford University.

Source: Purves, Orians, Heller, and Sadava, “Life: The Science of Biology,” Sinauer Associates/W.H. Freeman & Co., New York, 1999.

Reference: Blakemore, R. P., and Frankel, R. B., “Magnetic Navigation in Bacteria,” Scientific American, Dec. 1981, pp. 58 - 65.