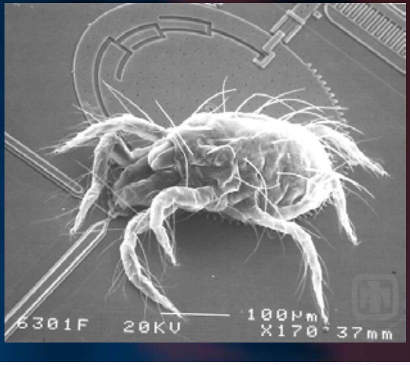
Microelectromechanical Systems (MEMS) based advanced high performance Radio Frequency (RF) systems

Outline

- Introduction
- What are MEMS
  - Why use MEMS – advantages
  - How are MEMS fabricated
  - MEMS actuation techniques
- RF MEMS
  - Fabrication
  - Applications
  - Advantages
  - MEMS switch library
  - Design and analysis
  - Failure mechanisms
  - Challenges
  - Conclusions

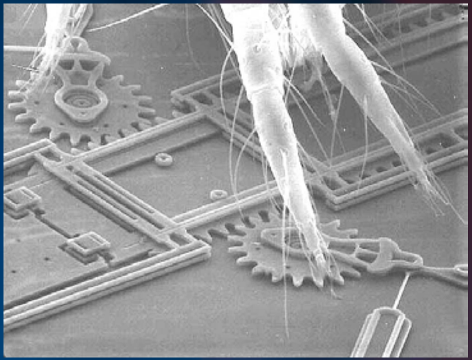
What are MEMS?

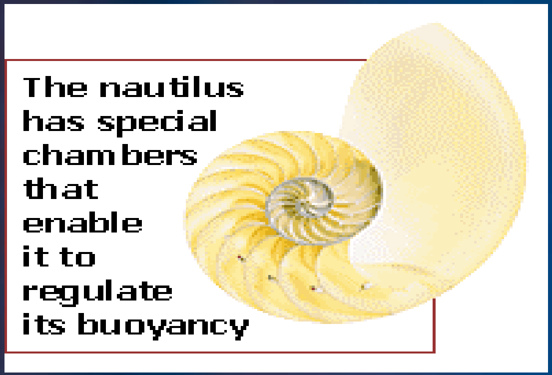
- MEMS are Micro Electro-Mechanical Systems
- MEMS typically have both electrical and mechanical components
- As microelectronics has shown, size doesn’t necessarily matter
- Envisioned by Sci-Fi authors
- R.P. Feynman – “There’s lots of room at the bottom”
- First MEMS Publication :
  - H.C. Nathanson, et al., The Resonant Gate Transistor, IEEE Trans. Electron Devices, March 1967, vol. 14, no. 3, pp 117-133
- Pressure sensors were the first MEMS products
  - Si diaphragms and diffused piezo-resistors
- Surface μ–machined accelerometers and flow sensors



Why MEMS?

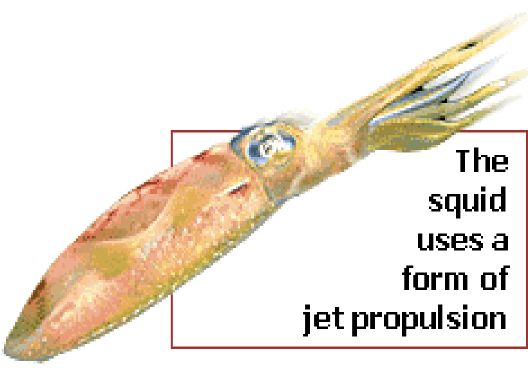
- Miniaturization with no loss of functionality
- Integration to form a monolithic system
- Improved reproducibility, reliability and accuracy
- Exploitation of new physics domains
- Low power
- Fast actuation techniques
- Improved selectivity and sensitivity
- MEMS may be the ONLY solution





The nautilus has special chambers that enable it to regulate its buoyancy

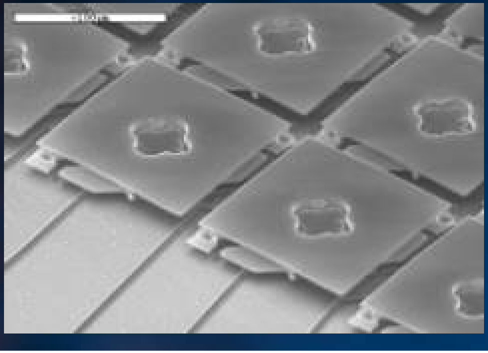
The ruby-throated hummingbird makes a 600-mile [1,000 km] journey on less than one tenth of an ounce [3 g] of fuel



The squid uses a form of jet propulsion

MEMS enables advances in many business areas…

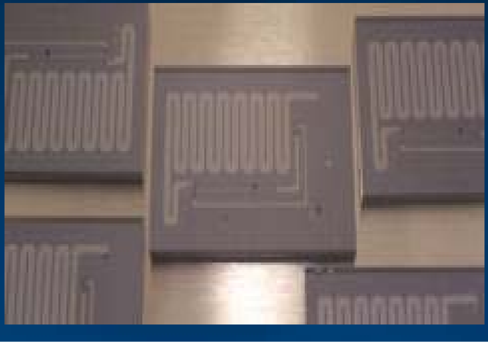
Optics



- **Micromirrors**
- **Silicon Benches**
- **Waveguided structures**
- **Integrated subsystems**

- Optical transparency
- Ease of manufacture
- High precision
- High reliability
- Integration of multiple subsystems

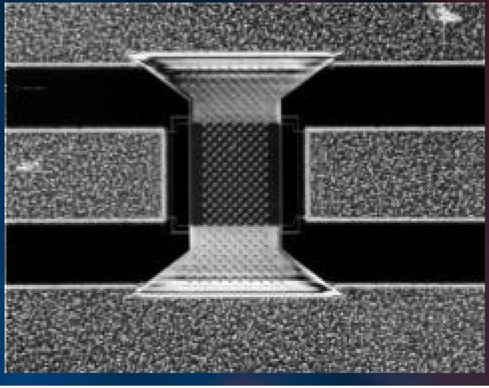
Life Sciences & Laboratory Equipment



- **Micronozzles**
- **Micropumps**
- **Membranes**
- **Microfluidic channels**
- **Wells & reservoirs**
- **Waveguides**
- **Lab-on-a-chip**

- Economical use of samples
- Low cost assays
- Quick turnaround on sample analysis
- Reduction in equipment footprint

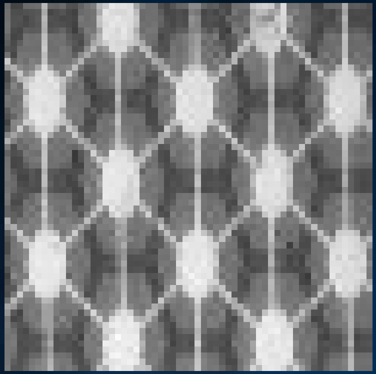
RF



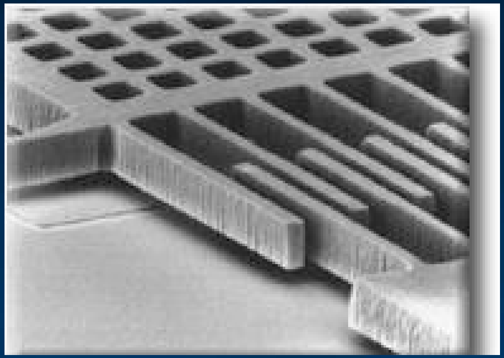
- **Capacitors**
- **High-Q inductors**
- **Resonators**
- **Relays and Switches**
- **Integrated subsystems**

- Low weight
- Low insertion loss
- High off-state isolation
- High precision
- Low power consumption
- High reliability

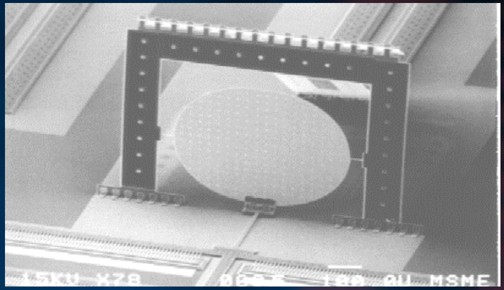
Some MEMS Applications



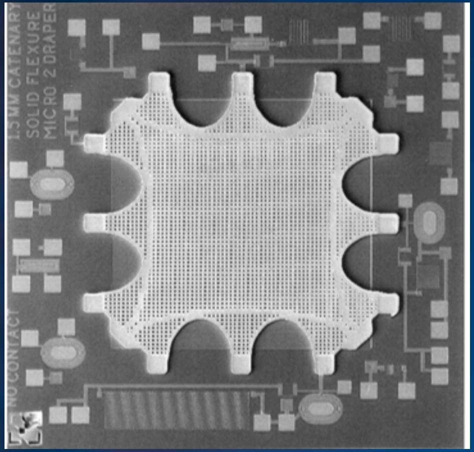
Ultrasound Transducer



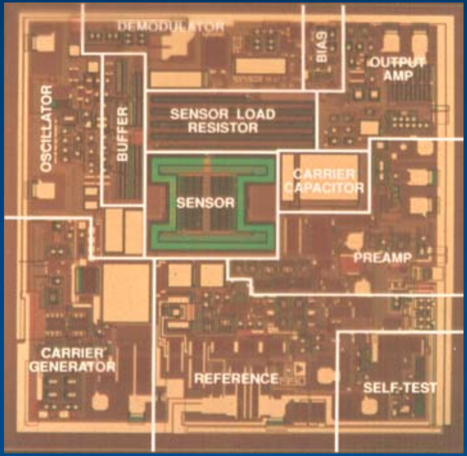
Gyroscope



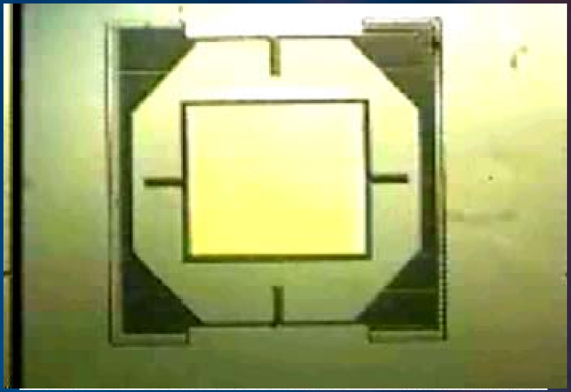
Optical Scanner



Microphone

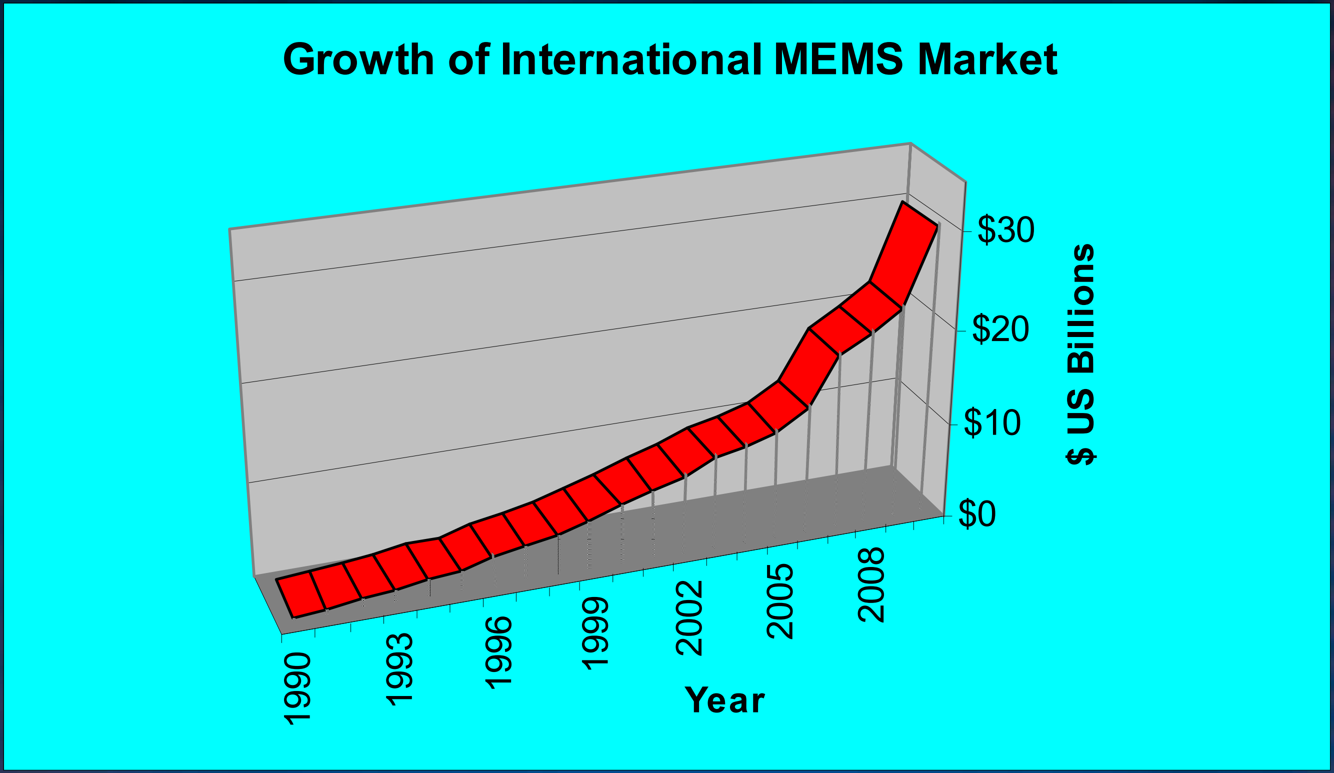


Accelerometer



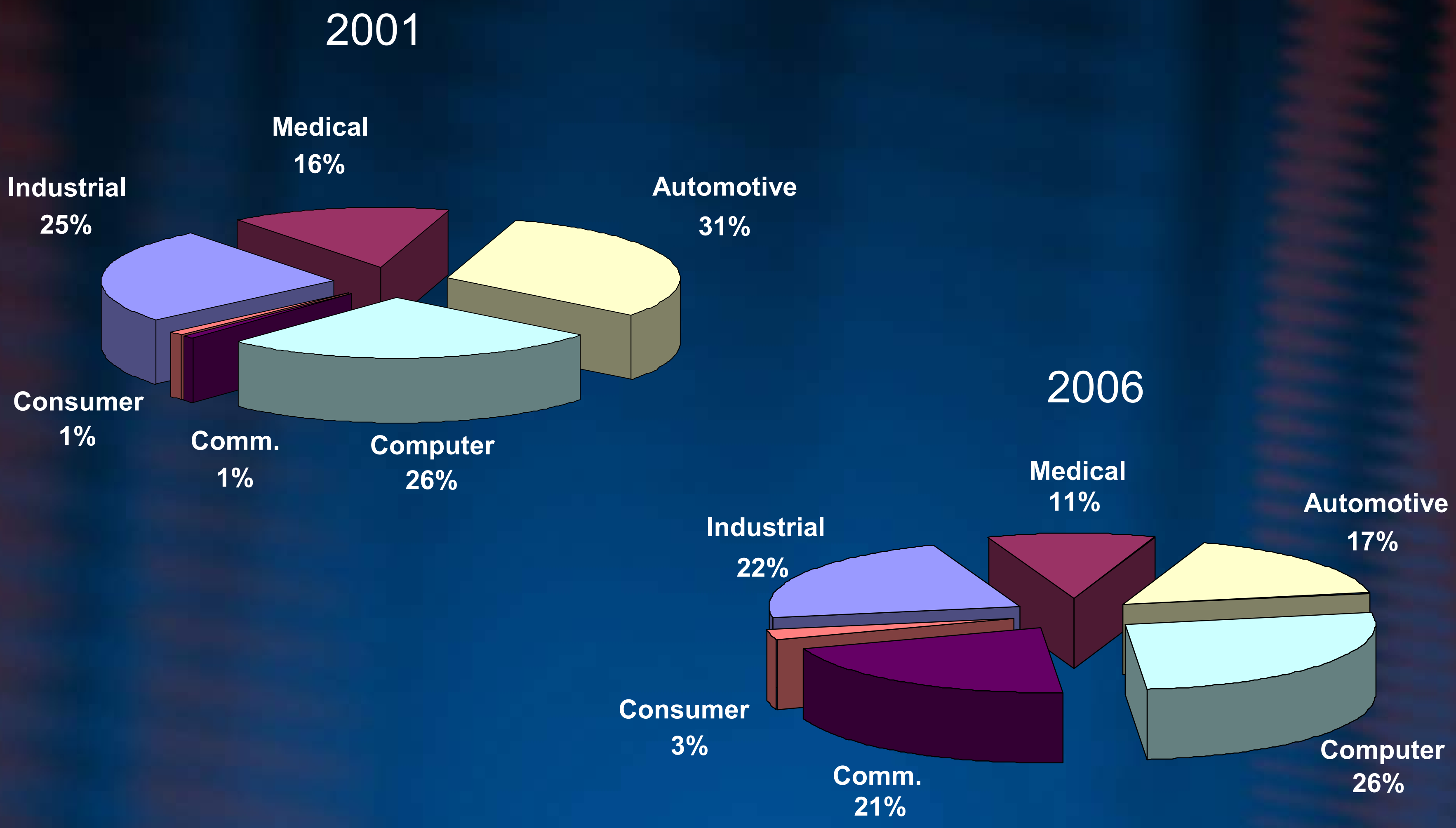
2-Axis Micromirror

Overall, the market is poised for breakaway growth



Source: Aggregate of data presented in MST News 5/01, including data from SPC, SRI, NEXUS, Batelle, VDC, and other research organizations

New applications for MEMS emerge and grow quickly



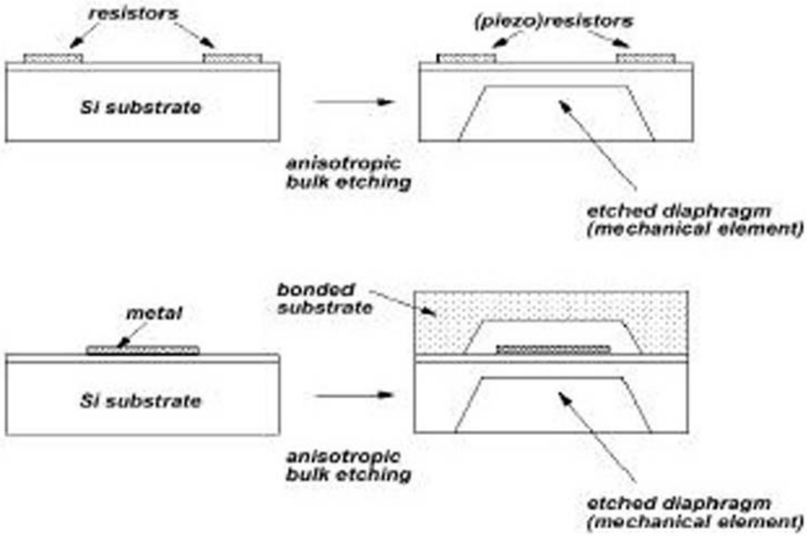
Source: In-stat 2002

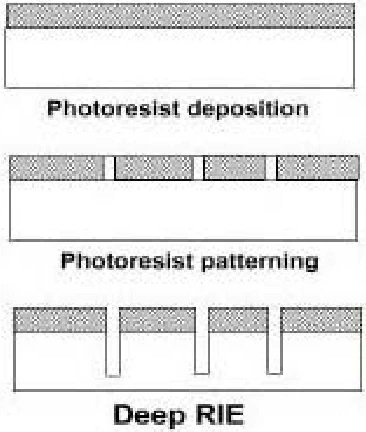
Fabrication of MEMS

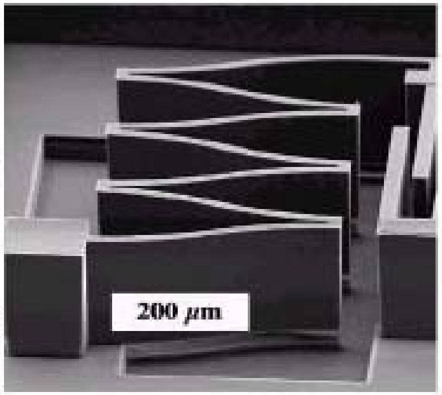
- Typically the fabrication of MEMS uses tools from the semiconductor industry, plus many other tools:
  - Photolithography
  - Diffusion
  - Oxidation
  - Etching (isotropic and anisotropic, wet and plasma)
  - Chemical Vapor Deposition (Si3N4, SiO2, Polysilicon, etc.)
  - Vacuum Metal Deposition (sputtering, evaporation)
  - Electroplating (LIGA, Ni, Au, Cu microstructures)
  - Chemical Mechanical Polishing to produce flat surfaces
  - Wafer Bonding, SOI wafers
  - Deep Plasma Etching (Inductively Coupled Plasma)
  - Sol-Gel deposition (PZT)

Bulk Micromachining

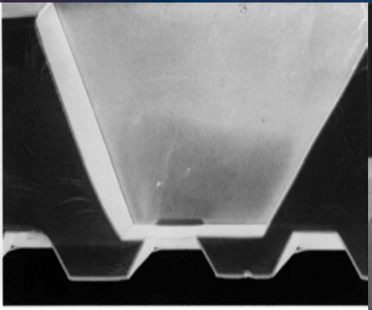
- Single Crystalline Silicon
- Isotropic Etching (HNA etc.)
- Anisotropic Etching (KOH, TMAH, EDP etc.)
- Reactive Ion Etching (RIE & DRIE)
- Accommodates sharp corners, small features and very smooth surfaces

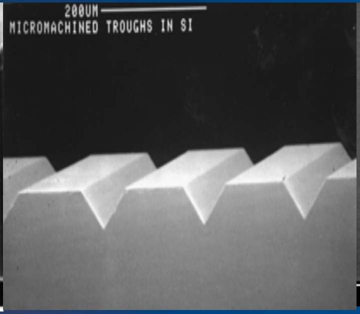


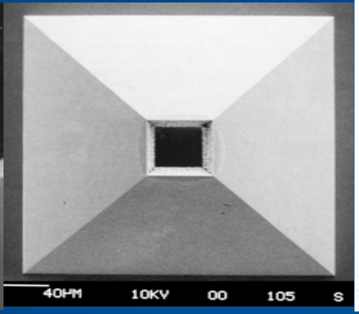




[1] R. Reay and G. Kovacs, Transducers' 95

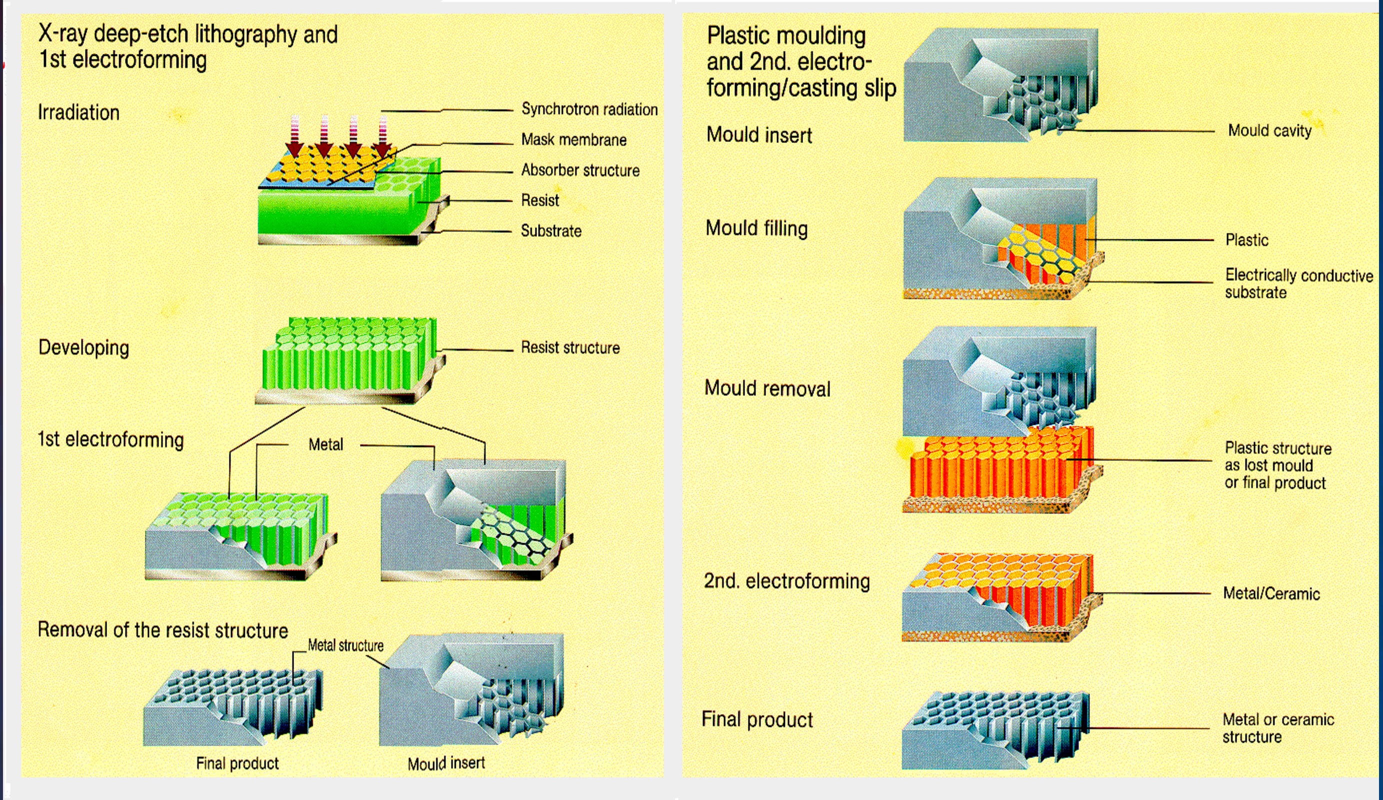


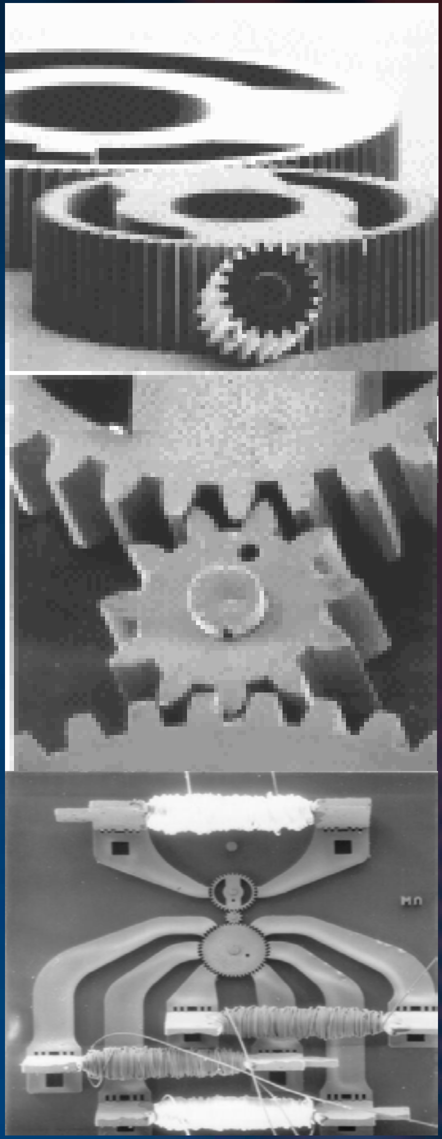




LIGA Process

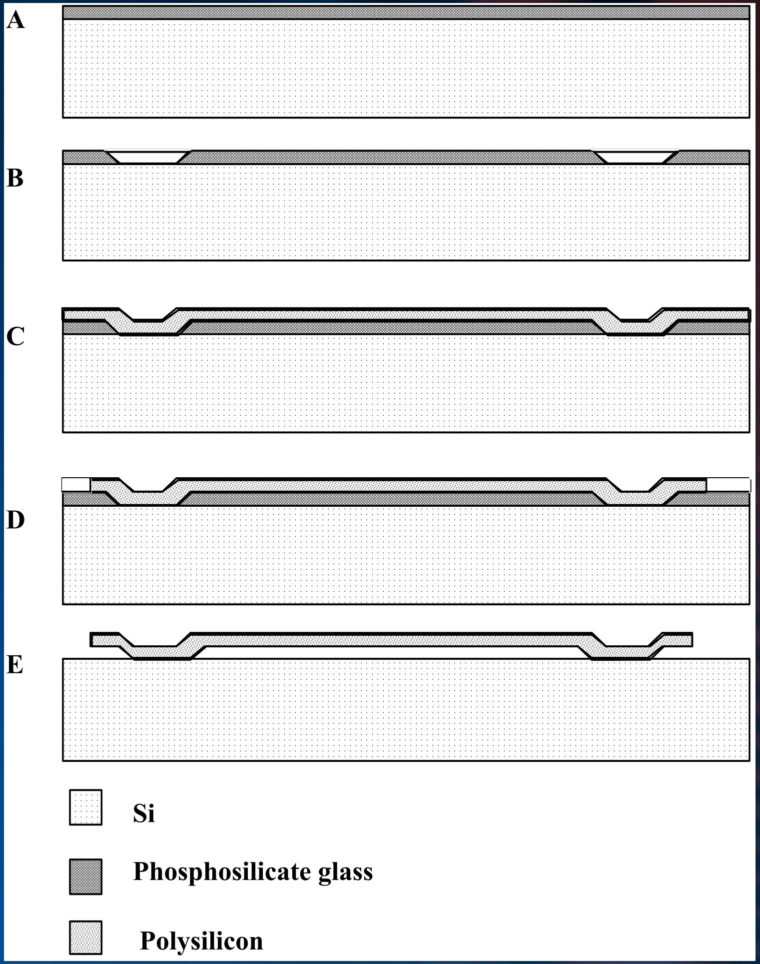
- Electroplated microstructures
- X-ray Photolithography in PMMA polymer resist
- Very high aspect ratio microstructures with smooth surfaces
- Used to create molds for low cost replication of precision shapes
- Molded diffraction grating for match-box spectrometer

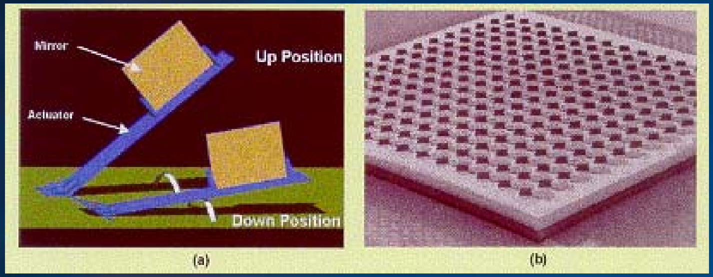


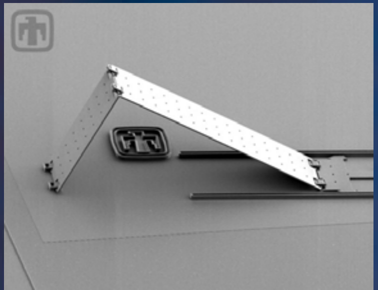


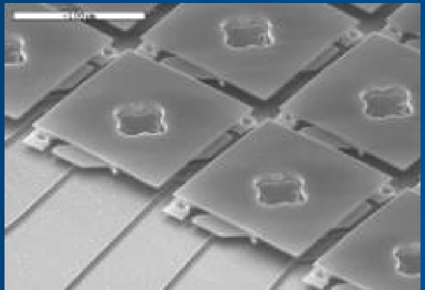
Surface Micromachining

- Primarily Poly-Si thin-film structures
- Make structures horizontally and erect them on a hinge
- MUMPS, SUMMIT, HEXSIL etc.
- Applications
  - Pop-up micro-mirrors
  - Pressure sensors
  - RF switches



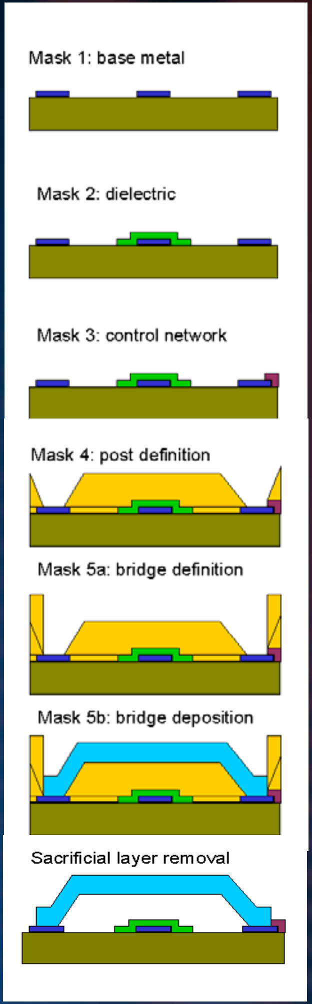






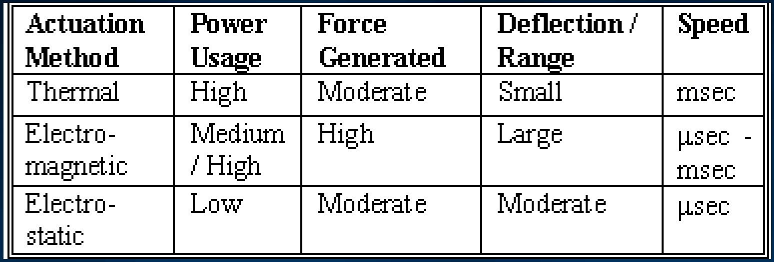
Capacitive MEMS RF Switch Fabrication

- Surface micromachining based fabrication process
  - oxide deposition, electrode, dielectric deposition and patterning
  - metal posts deposition and patterning
  - spacer coating and patterning
  - membrane deposition and patterning
  - removal of spacer layer by dry or wet etching*



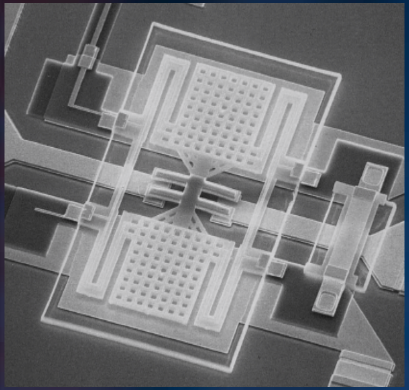
*Yao, Z., Chen, S., Eshelman, S., Goldsmith, C., "Micromachined low-loss microwave switches", *IEEE, J. MEMS*, Vol 8, pp 129–34, 1999

MEMS Actuation Techniques



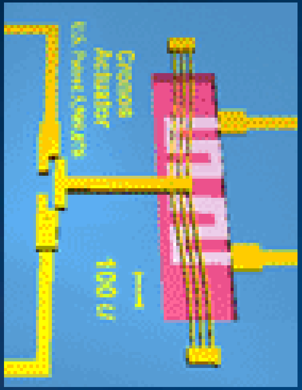
Actuation Method	Power Usage	Force Generated	Deflection / Range	Speed
Thermal	High	Moderate	Small	msec
Electro-magnetic	Medium / High	High	Large	µsec - msec
Electro-static	Low	Moderate	Moderate	µsec

Mechanism
Advantage
Disadvantage



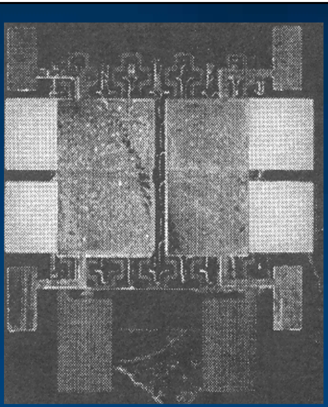
Rockwell

Electrostatic
Fast
High voltage



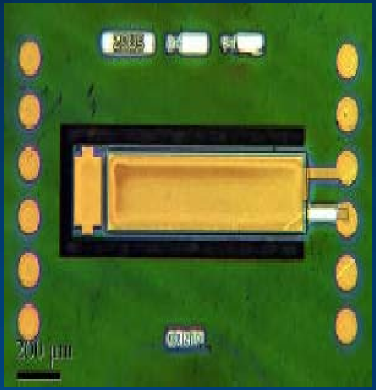
Cronos

Thermal
High force,
bi-directional
Quiescent
power,
slow



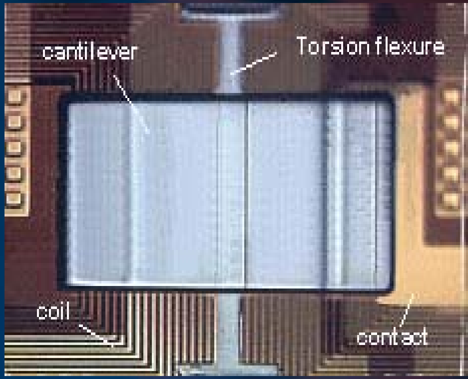
Georgia Tech

Magnetostatic
Fast,
high force,
bi-directional
Quiescent
power



Marconi

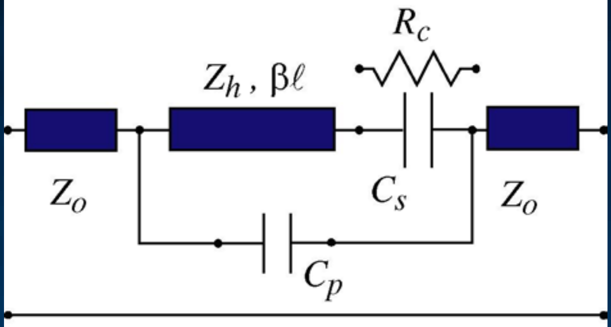
Piezoelectric
Fast
Small throw

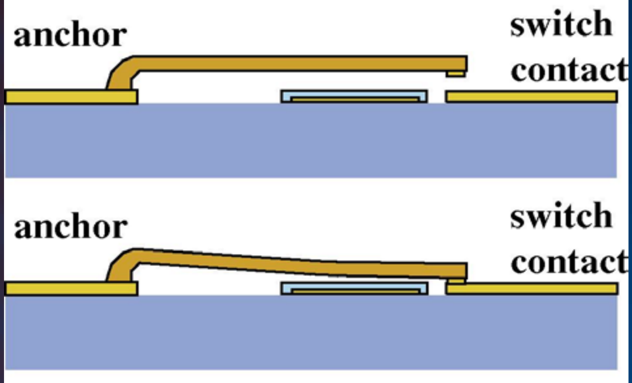


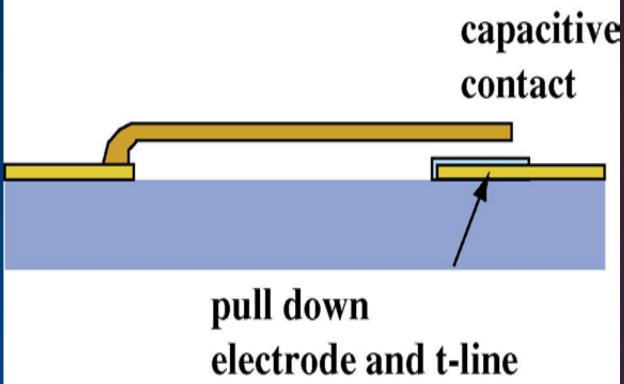
Microlab

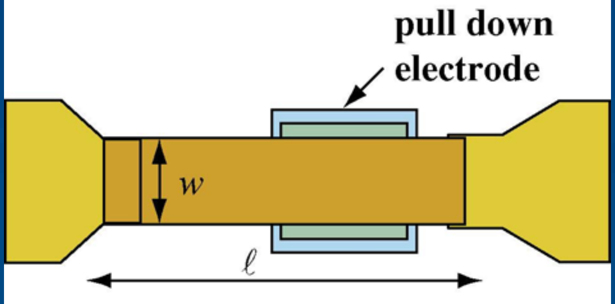
Latching
Magnetic
Fast,
high force,
bi-directional
Construction

Series Switches

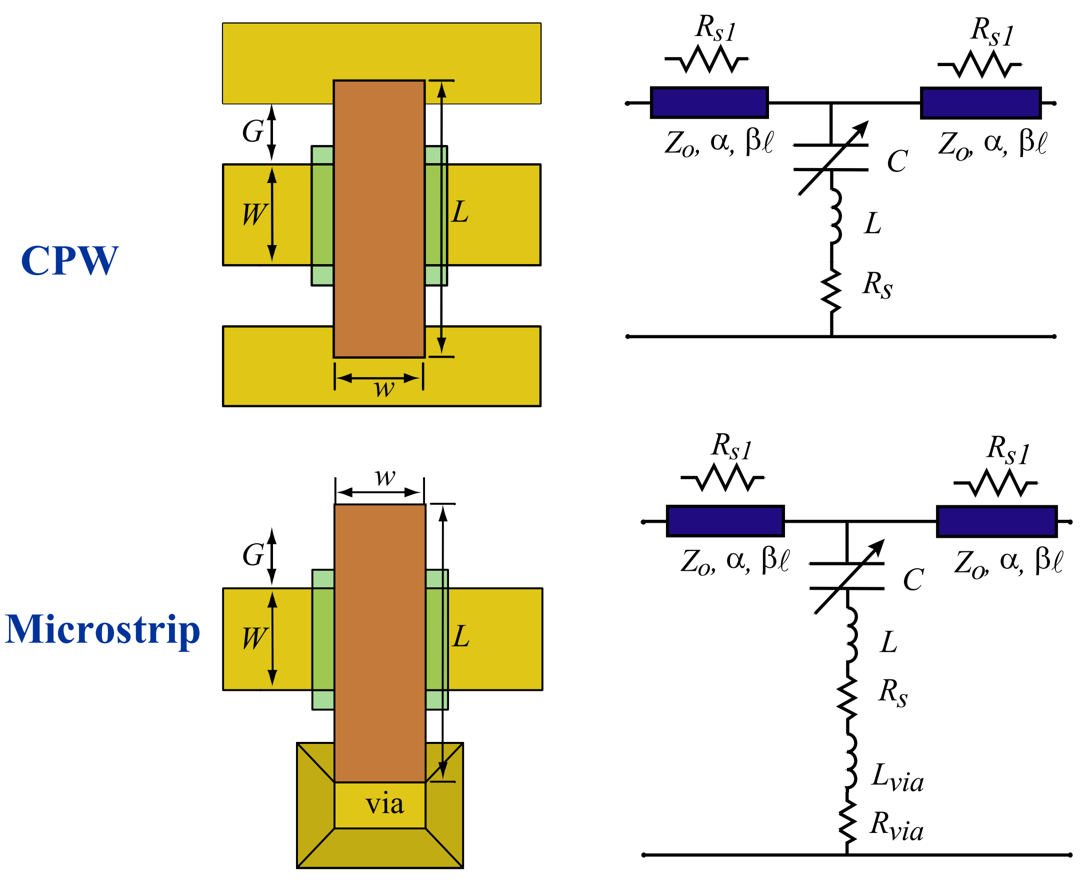


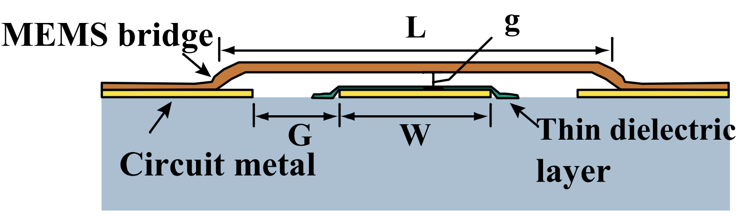






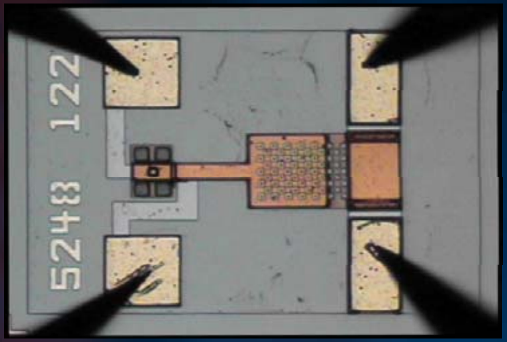
Shunt Capacitive Switches



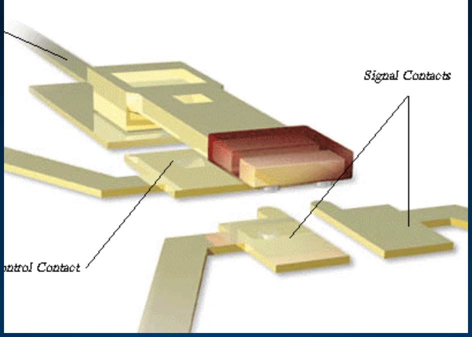


MEMS Ohmic Switch Technology

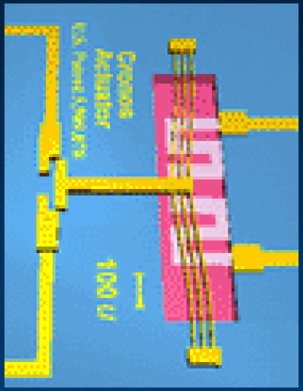
HRL Laboratories

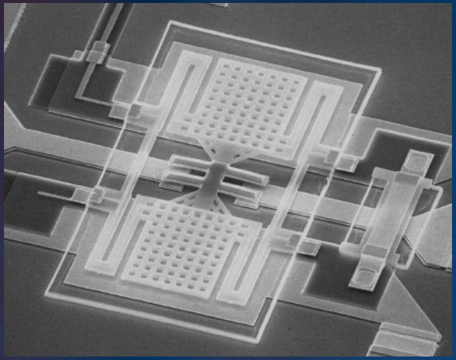


Analog Devices

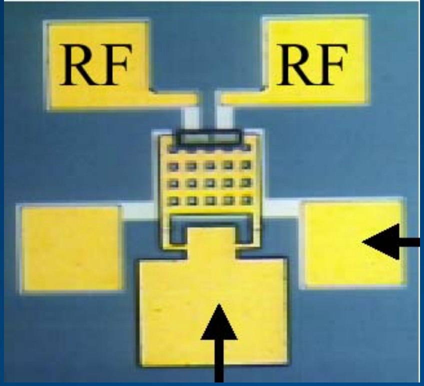


Chronos

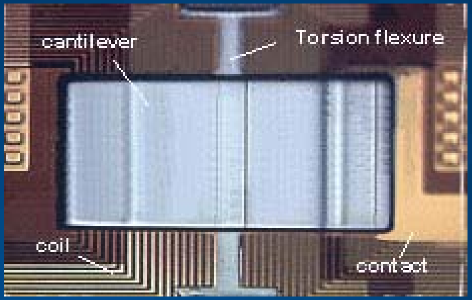




Rockwell



Motorola



Microlab

Ohmic Contact Switch Companies

Rockwell Scientific
HRL Laboratories
Analog Devices
Motorola
Chronos
Omron
Microlab
Several standard MEMS fabs

Switch Construction

Metallizations

Gold, aluminum, nickel

Substrates

Silicon, gallium arsenide

Actuation Mechanisms

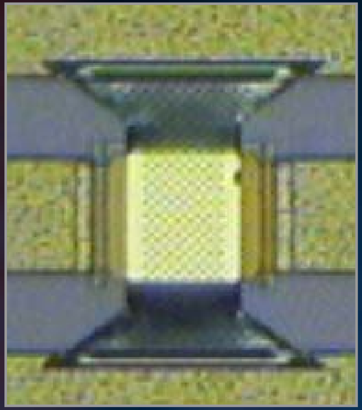
Electrostatic, thermal, magnetic

Co-integration

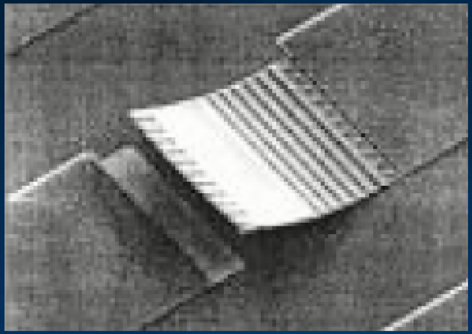
microwave electronics

MEMS Capacitive Switch Technology

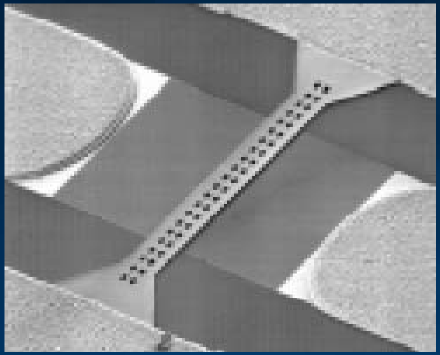
Raytheon

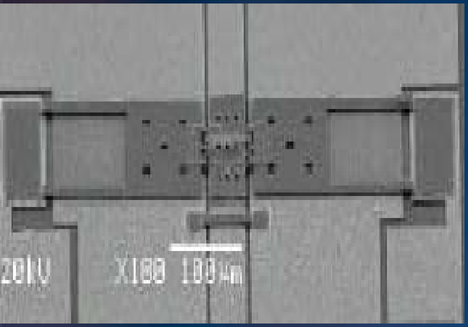


MIT Lincoln Labs

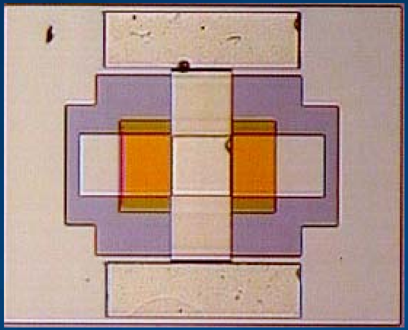


Bosch

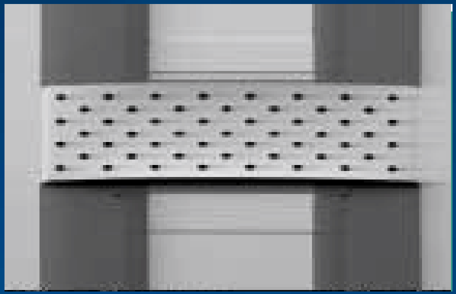




Samsung



LG Electronics



Daimler-Chrysler

Capacitive Contact Switch Companies

Raytheon
Northrop-Grumman
Samsung
LG Electronics
MIT Lincoln Labs
Daimler-Chrysler
Bosch

Switch Construction

Metallizations

Gold, aluminum, copper

Substrates

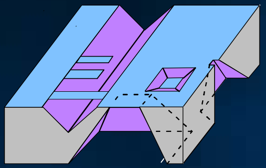
Silicon, quartz, gallium arsenide

Co-integration

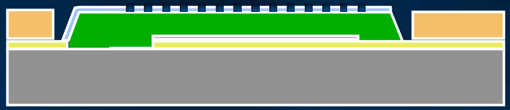
CMOS

Radio Frequency Applications

Technology



Bulk Micromachining



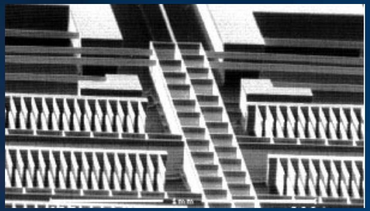
Surface Micromachining

Micromachining - fab of 3D structures on an IC

MEMS - movable structure micromachined into an IC

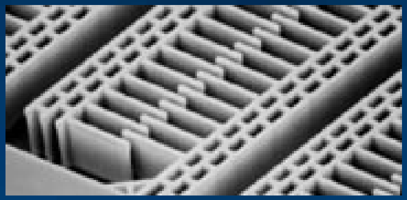
Devices

Cornell



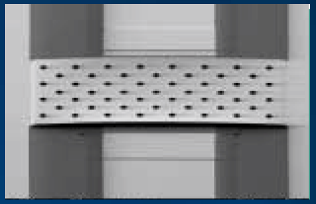
Transmission Lines

Rockwell



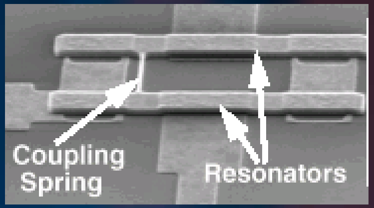
Variable Capacitor

Daimler-Chrysler



Switch

U Michigan

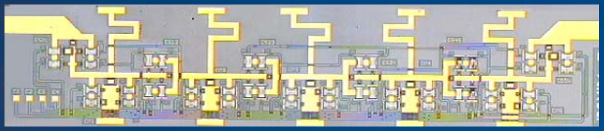


Filter

These devices are the "transistor" of a new generation of mechanical IC devices!

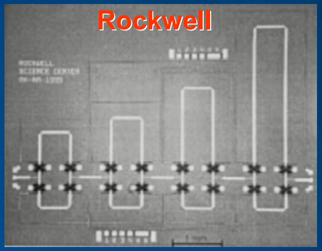
Circuits

Raytheon



5-Pole Bandpass Filter

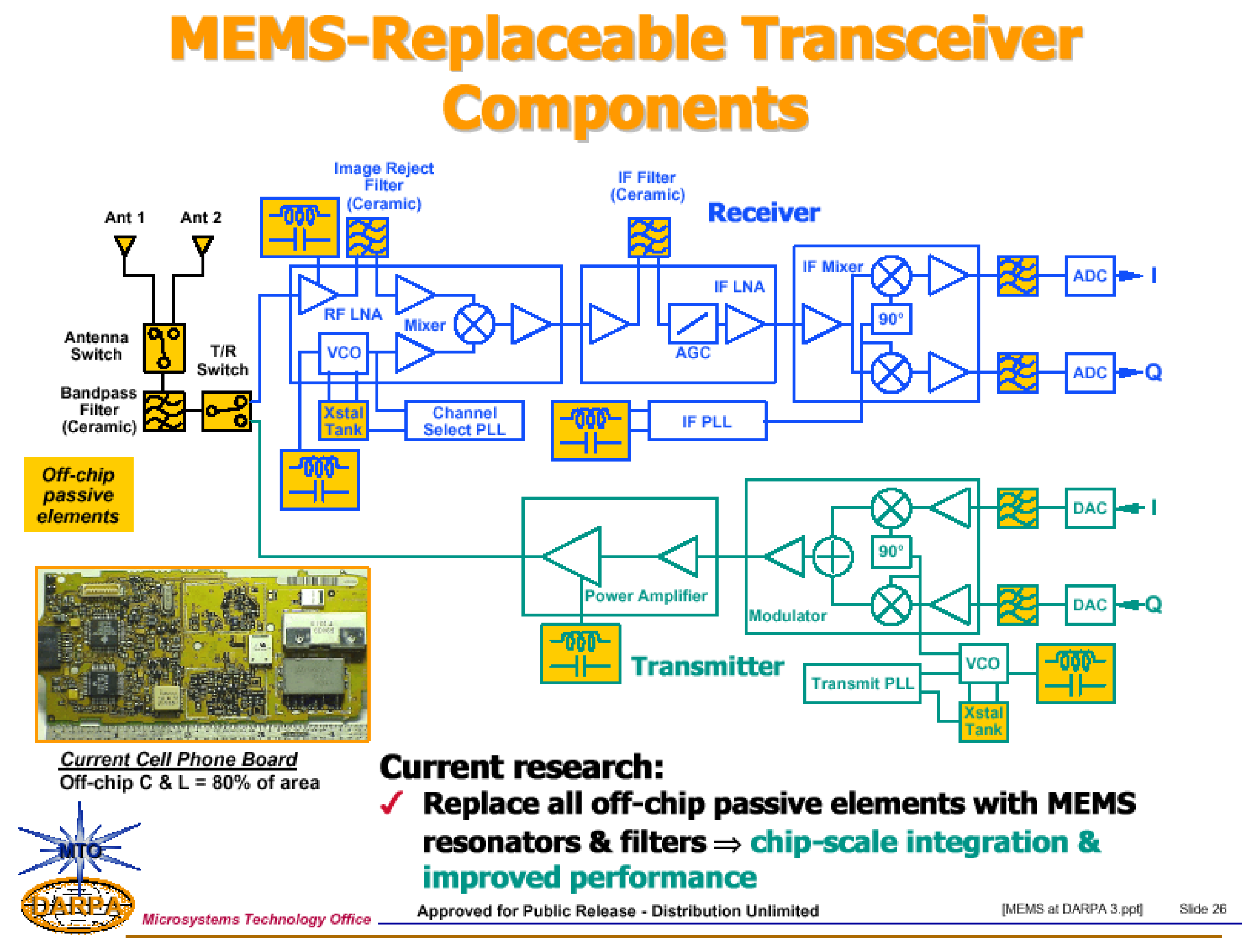
Rockwell



Electronic Phase Shifter

MEMS are creating a revolutionary impact on RF technology!

Opportunity for Applications of RF MEMS



MEMS-Replaceable Transceiver Components

Current Cell Phone Board

Off-chip C & L = 80% of area

Current research:

- ✓ **Replace all off-chip passive elements with MEMS resonators & filters ⇒ chip-scale integration & improved performance**

Microsystems Technology Office

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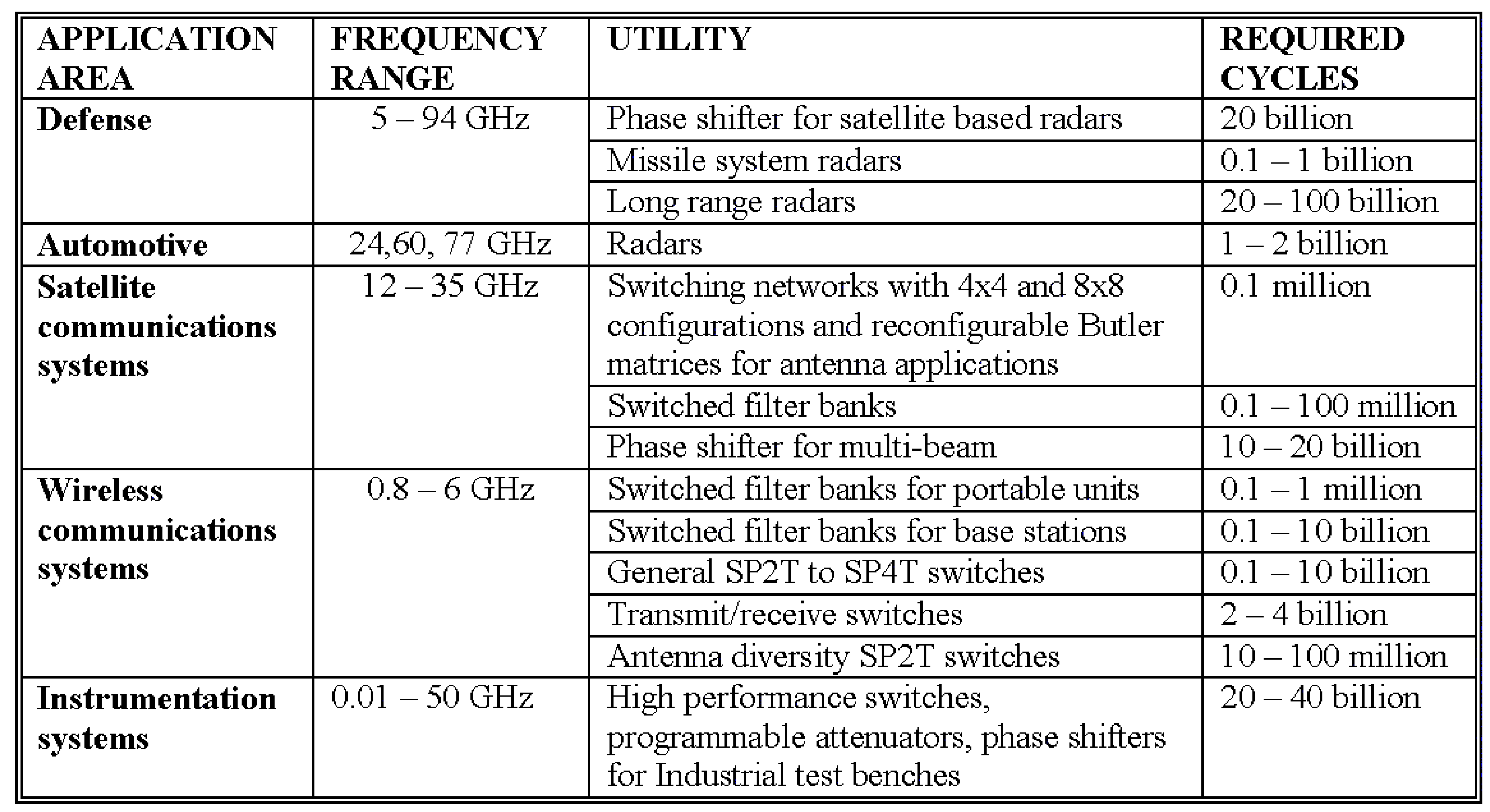
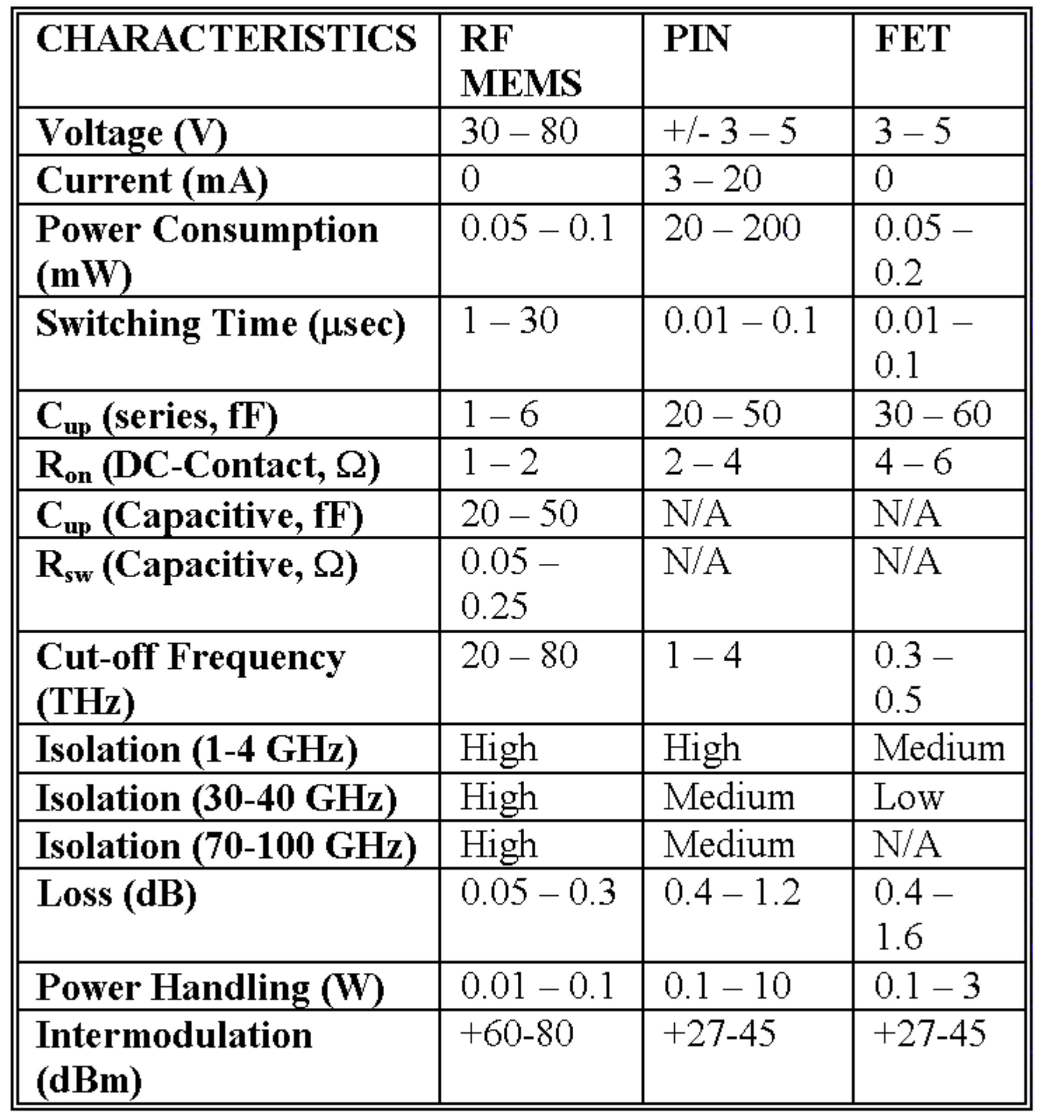
Application Areas for MEMS RF



APPLICATION AREA	FREQUENCY RANGE	UTILITY	REQUIRED CYCLES
Defense	5 – 94 GHz	Phase shifter for satellite based radars	20 billion
		Missile system radars	0.1 – 1 billion
		Long range radars	20 – 100 billion
Automotive	24,60, 77 GHz	Radars	1 – 2 billion
Satellite communications systems	12 – 35 GHz	Switching networks with 4x4 and 8x8 configurations and reconfigurable Butler matrices for antenna applications	0.1 million
		Switched filter banks	0.1 – 100 million
		Phase shifter for multi-beam	10 – 20 billion
Wireless communications systems	0.8 – 6 GHz	Switched filter banks for portable units	0.1 – 1 million
		Switched filter banks for base stations	0.1 – 10 billion
		General SP2T to SP4T switches	0.1 – 10 billion
		Transmit/receive switches	2 – 4 billion
		Antenna diversity SP2T switches	10 – 100 million
Instrumentation systems	0.01 – 50 GHz	High performance switches, programmable attenuators, phase shifters for Industrial test benches	20 – 40 billion

Comparison: MEMS versus Solid-state switches



CHARACTERISTICS	RF MEMS	PIN	FET
Voltage (V)	30 – 80	+/- 3 – 5	3 – 5
Current (mA)	0	3 – 20	0
Power Consumption (mW)	0.05 – 0.1	20 – 200	0.05 – 0.2
Switching Time (μsec)	1 – 30	0.01 – 0.1	0.01 – 0.1
C_{up} (series, fF)	1 – 6	20 – 50	30 – 60
R_{on} (DC-Contact, Ω)	1 – 2	2 – 4	4 – 6
C_{up} (Capacitive, fF)	20 – 50	N/A	N/A
R_{sw} (Capacitive, Ω)	0.05 – 0.25	N/A	N/A
Cut-off Frequency (THz)	20 – 80	1 – 4	0.3 – 0.5
Isolation (1-4 GHz)	High	High	Medium
Isolation (30-40 GHz)	High	Medium	Low
Isolation (70-100 GHz)	High	Medium	N/A
Loss (dB)	0.05 – 0.3	0.4 – 1.2	0.4 – 1.6
Power Handling (W)	0.01 – 0.1	0.1 – 10	0.1 – 3
Intermodulation (dBm)	+60-80	+27-45	+27-45

Advantages of RF MEMS

Performance

- Ultra-low RF loss – Beats any available electronics technology for switching or tuning of RF signals
- Essentially no DC power consumption – Perfect for battery and low power-consumption applications
- Extremely high linearity – Creates no harmonics or distortion, excellent for broadband communications

Size

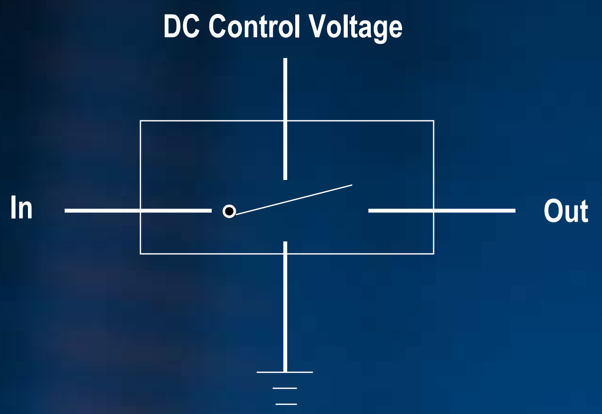
- Microminiature size – Reduced size with unmatched performance, able to work at very high frequencies (> 50 GHz)
- Tunability – Supports reduction in number of passive components, combines numerous switched parts into one tunable chip

Cost

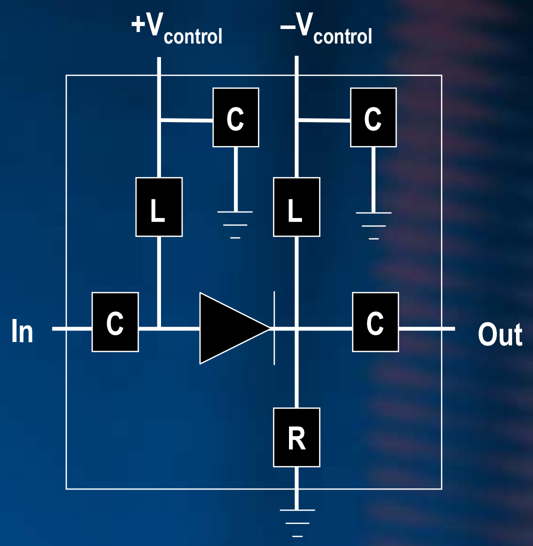
- Reduced IC costs – Low cost, batch fabrication. Much less expensive than competing exotic semiconductor technologies.
- Significant system cost impact - Able to be combined with other electronics for "system-on-a-chip." Improved functionality can greatly reduce cost.

RF MEMS Switches Are Much Simpler than PIN Diode Switches

RF MEMS Switch Circuit



PIN Diode Switch Circuit

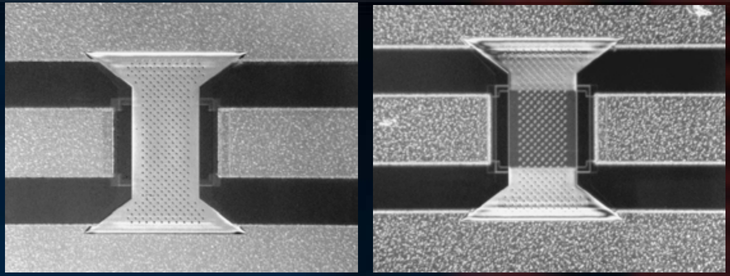


0.0025 sq inch	Area	0.25 sq inch
One	DC Control Voltages	Two: + and –
< 1 nanowatt	DC Control Power	~300 milliwatts

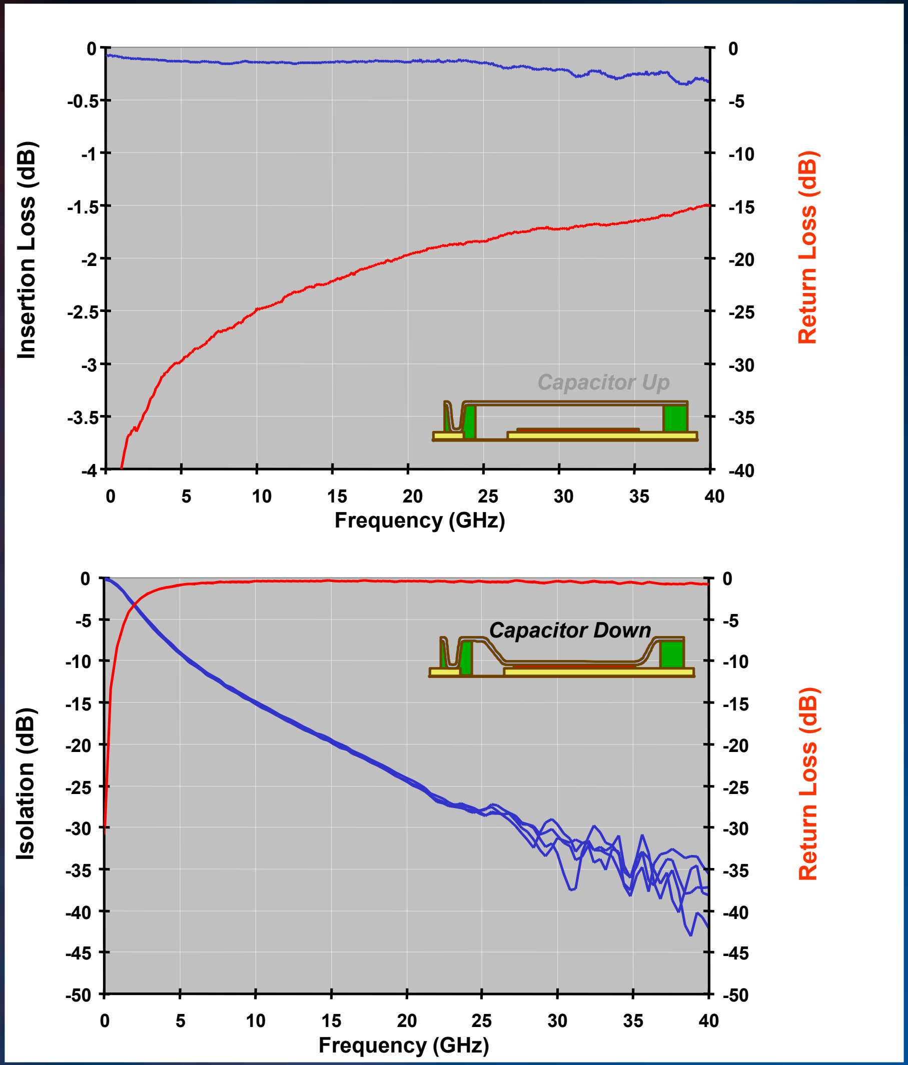
Companies/ Univ./Labs Developing MEMS switches

- Raytheon / (Texas Instruments)
- Raytheon / (HRL)
- Rockwell Science Center
- Northrop Grumman
- Motorola
- Analog Devices
- Lincoln Labs
- Dow-Key Microwave (with HRL)
- Sarnoff Labs
- Sandia Labs
- Bosch, Germany
- DaimlerChrysler, Germany
- Thompson-CSF, France
- University of Michigan
- Univ. of Illinois, Urbana
- Univ. of California, Berkeley
- Northeastern University
- And other small efforts at many European and Japanese Univ.
- Samsung, Korea
- Sony, Japan
- MEMSCAP, France
- Corning IntelliSense
- LG-Corporate Research, Korea
- NEC, Japan

DEVICE CHARACTERISTICS AND PERFORMANCE	**ROCKWELL [16,17]**	**RAYTHEON /TI [18,19,20]**	**HRL LABS [21,22]**	**U. MICH. [23]**	**SIEMENS AG [29]**	**OMRON [30]**	**NEC [31]**	**NORTHEASTERN U. [26,27,28]**
MEMS technology	Surface	Surface	Surface	Surface	Bulk	Bonded wafer	Bonded wafer	Surface
Device size (µmxµm)	80 x 160	120 x 280	~120 x 300	~1000x2000	1.5 (mm^2)	2000x2500	250 x 900	Beam = 30 x 65
Current handling (mA)	200	N/A	140	N/A	>100	N/A	N/A	150
Structural material	SiO_2	Al alloy	Si_xN_y	Plated Au	Silicon epi	Silicon	P++ Silicon	Au/Ni
Actuation mechanism	Electrostatic (ES)	ES	ES	ES	Wedge ES	ES	ES	ES
Actuation voltage (V)	~60	~50	~25	15-20	24	16-19	125	30-300
Contact mechanism	Au	Capacitive	Au	Capacitive	Plated Au alloy	Au	Au	Au
Insertion loss (dB)	0.2 (dc-40GHz)	0.15 at 10 GHz 0.28 at 40 GHz	0.2 (dc-40GHz)	0.6 (22-38 GHz)	Not available	Not available	0.2 at 30 GHz	N/A
Isolation (dB)	-32 at 10 GHz -22 at 40 GHz	-15 at 10 GHz -35 at 35 GHz	-40 at 12 GHz -27 at 40 GHz	-40 at 22 GHz -50 at 35 GHz	Not available	Not available	-13 at 30 GHz	N/A
Switching time	2-5 µs	3.5-5.3 µs	20 µs	Not available	< 0.2ms	< 0.3ms	-	150 kHz cutoff
Lifetime (million cycles)	~100 (cold) 10s (hot 1-40mA)	500	~4 (hot 10mA)	N/A	N/A	1-10 (hot 10mA)	-	0.01-1000 (cold)

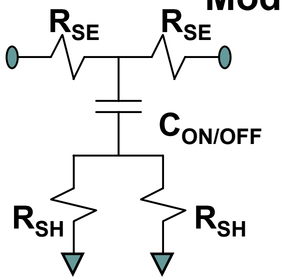


Raytheon



Insertion Loss @ 40 GHz	<0.07	dB
Isolation @ 40 GHz	>35	dB

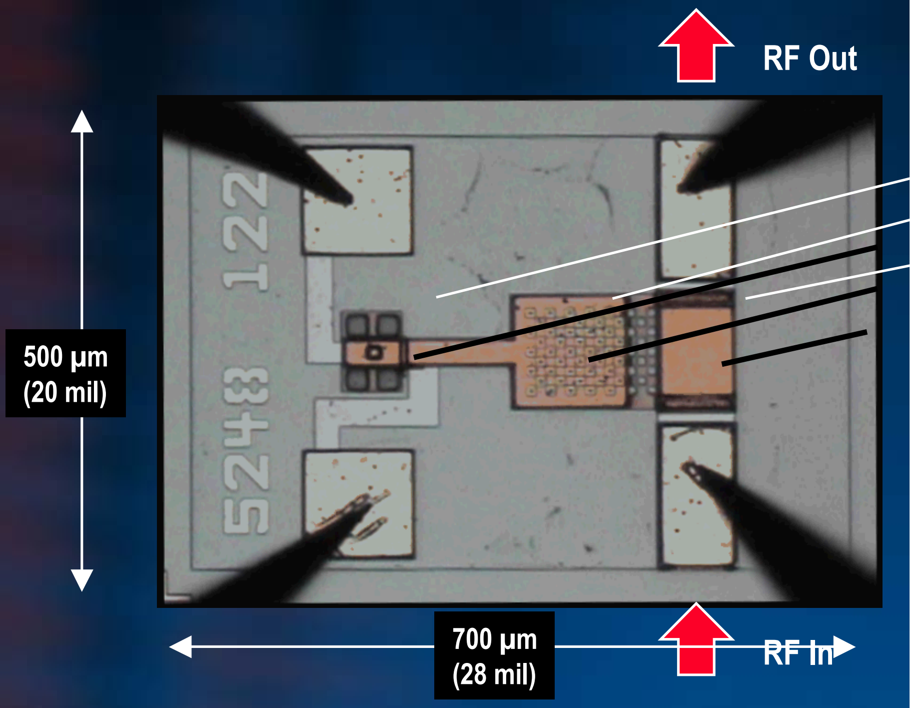
Model Values



Rs	0.11	Ohms
Rsh	0.2	Ohms
Coff	0.03-0.045	pF
Con	3.4	pF
Ron	0.25	Ohms
Capacitance Ratio	70-110	
Cutoff Frequency	18,000	GHz
Switching Speed	< 10	µs
Intercept Point	> +66	dBm
Switching Voltage	30-50	volts
Size	280 × 170	µm

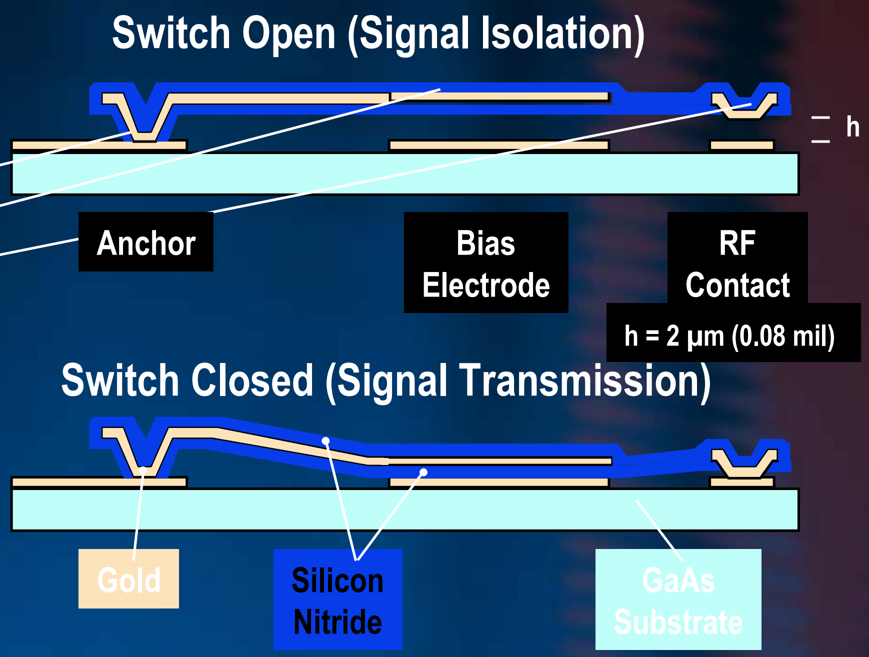
HRL

Top View



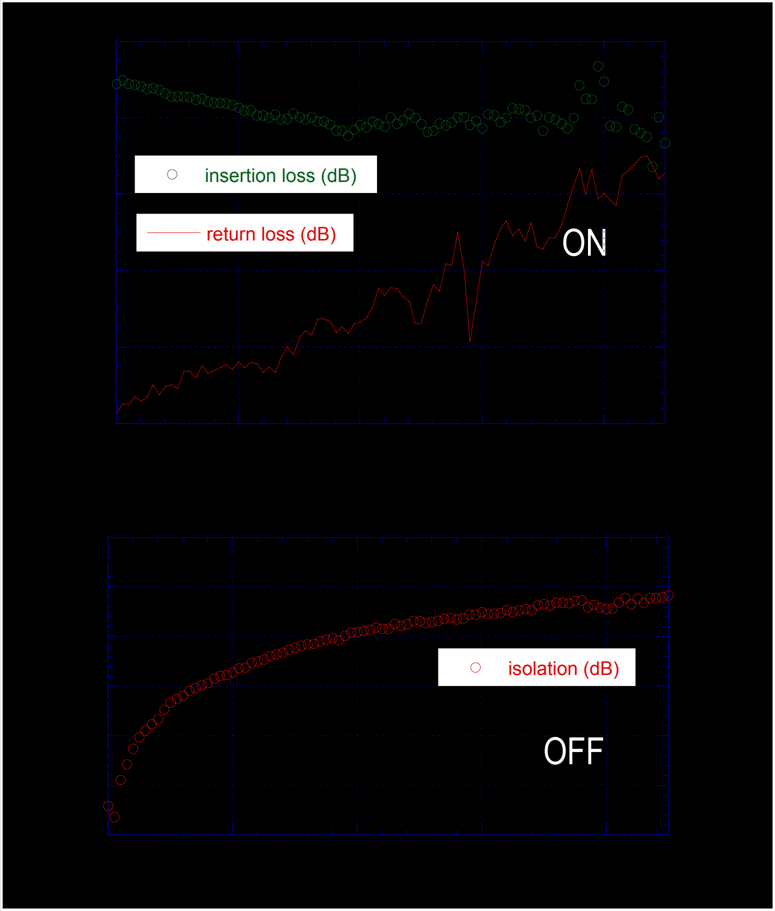
- Metal-Metal contact series switch
- Electrostatic actuation: 20–40 V
- Switching time: 20–40 µsec
  - Depends on gap and voltage

Side View

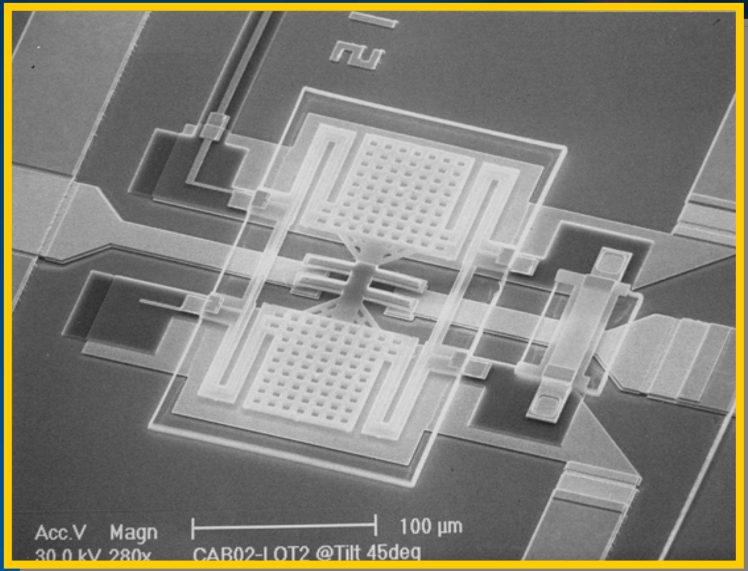


- Nitride/gold/nitride tri-layer prevents creep
- Fabrication process is compatible with other substrate materials like high resistivity silicon

Rockwell Science Center

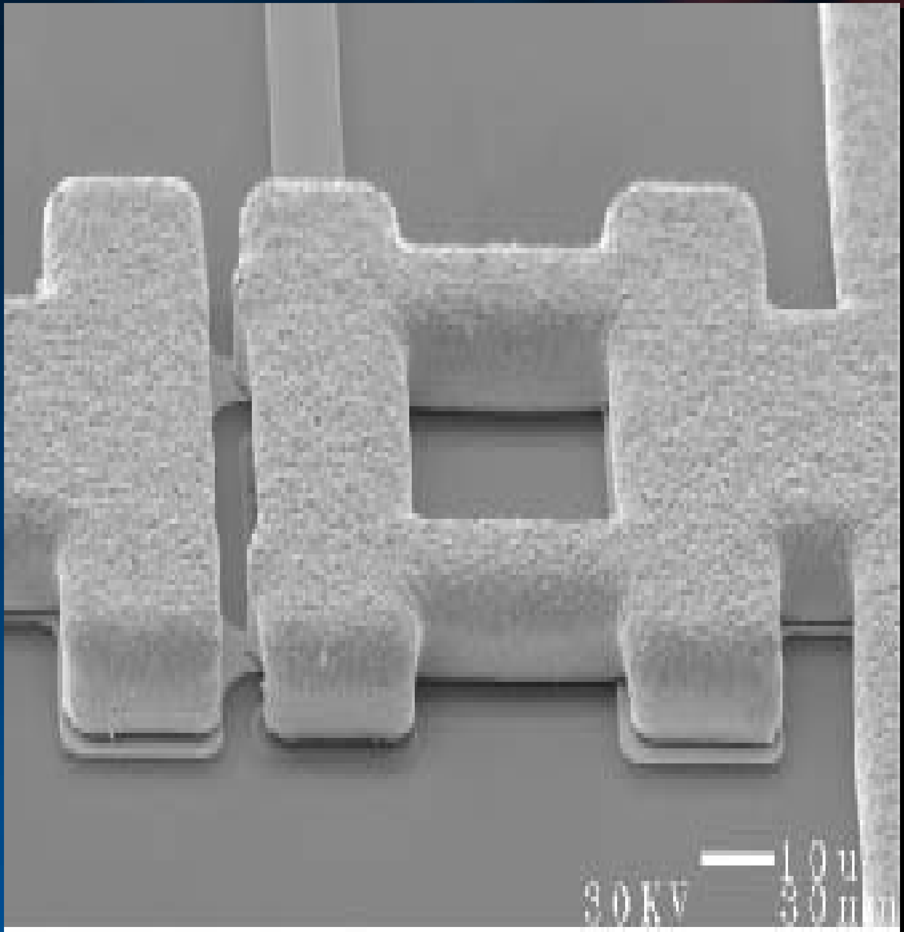


- Low insertion loss: 0.1 dB @ 2GHz
- Excellent Isolation: -56dB @2 GHz
- Turn-on time <10μs
- +28dBm power handling capability
- Third order intercept 80dBm
- Implementation on Si, GaAs, Quartz

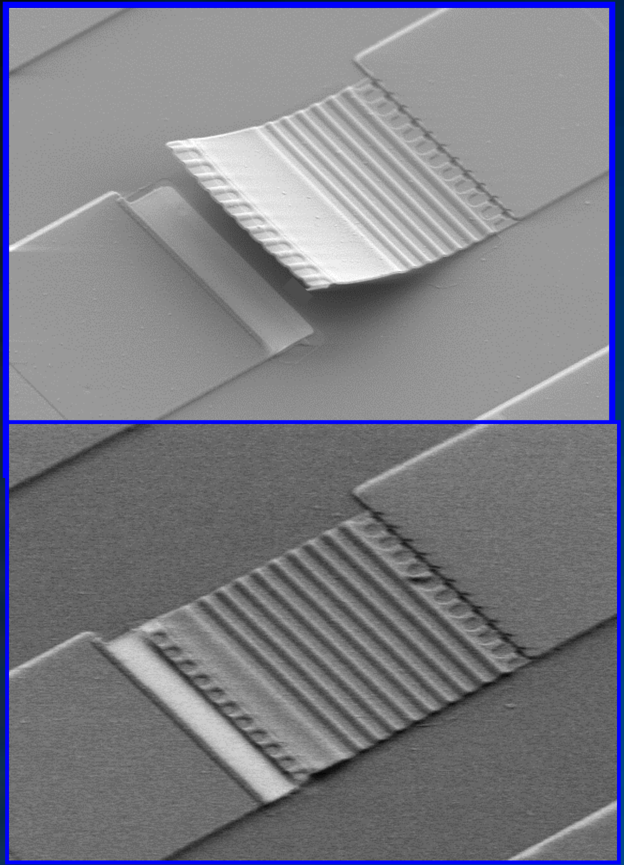


Analog Devices

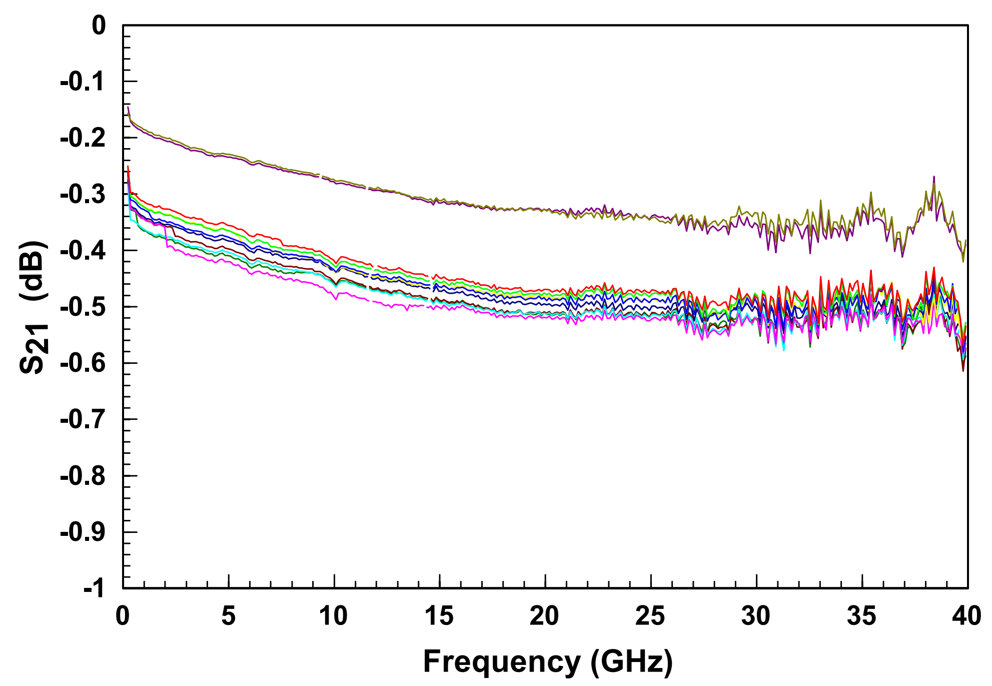
- DC Contact Series switch
- Vp = 50-60 V
- Isolation: -40 dB (4 GHz)
- t = 0.5-3 ms
- Isolation: -27 dB (20 GHz)
- Cu = 4 fF
- Loss : -0.1 to –0.2 dB (DC-20 GHz)
- Rs = 1-2 Ω
- (Electrode does not touch cantilever)



MIT Lincoln Lab



DC Contact single switch in CPW configuration

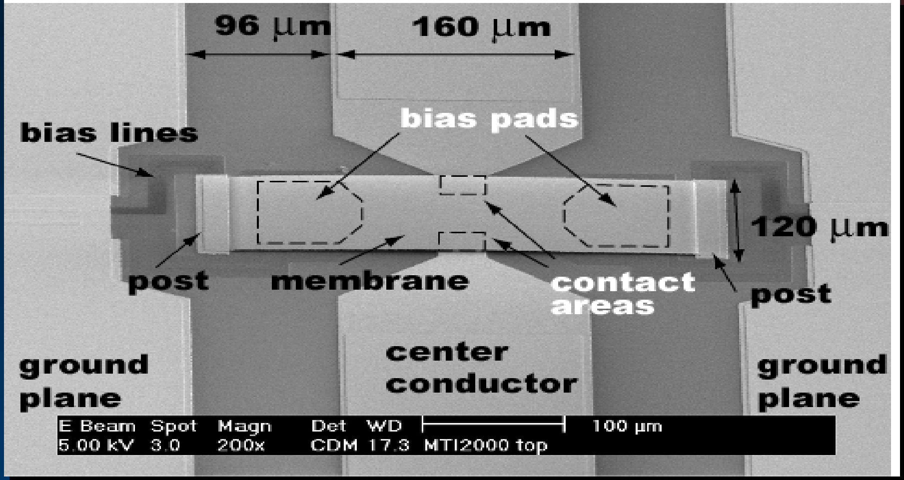


RF Measurement (9 Switches)

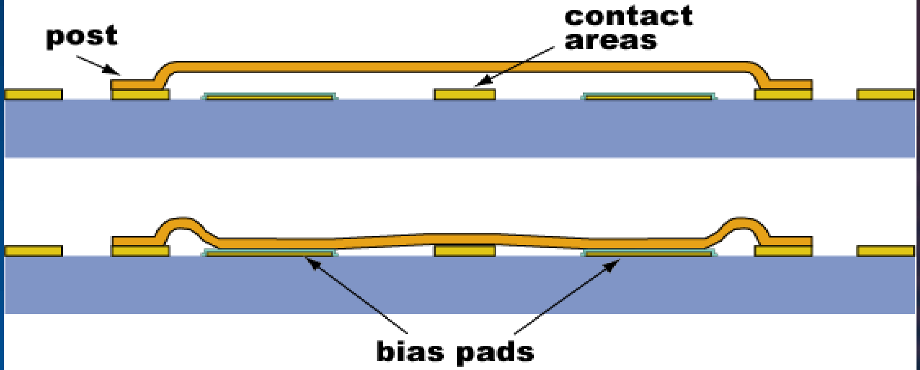
Contact Resistance:	95% yield < 2 Ω 60% yield < 1 Ω
Switch Speed:	Closing time: < 1 μs Opening time: < 1 μs

University of Michigan

- All metal series switch
- Vp=20-25 V
- Switching speed = 10 us
- Cu=4-8 fF, Ron=0.5-2 Ohms
- Isolation: -36 to –40 dB (4 GHz)
- Compact Geometry
  - 300 um by 100 um
- CPW or Micro-strip
- High Impedance Bias Line
  - 1 kOhm / square SiCr



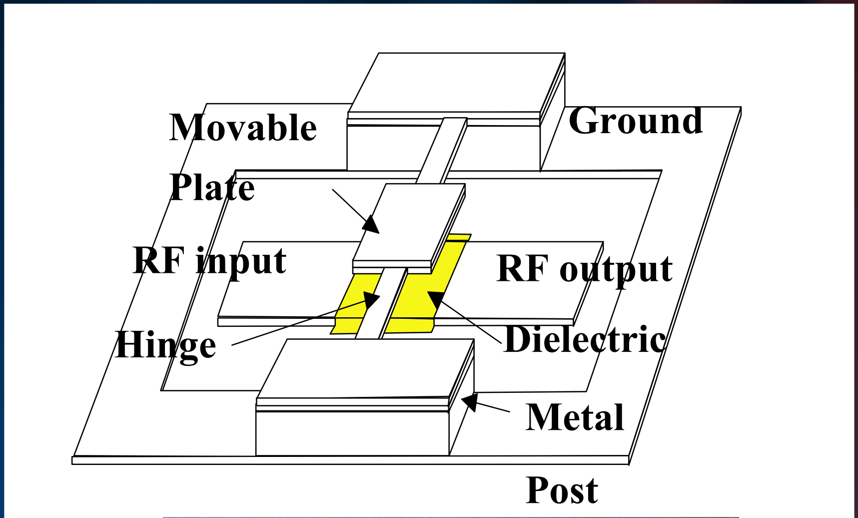
Cross Section

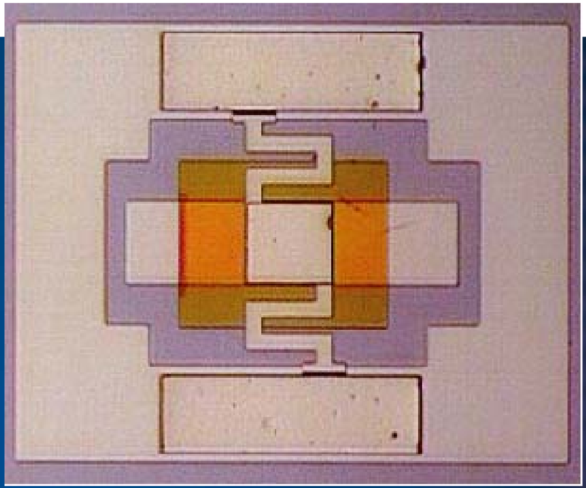


Muldavin/Rebeiz

LG Korea

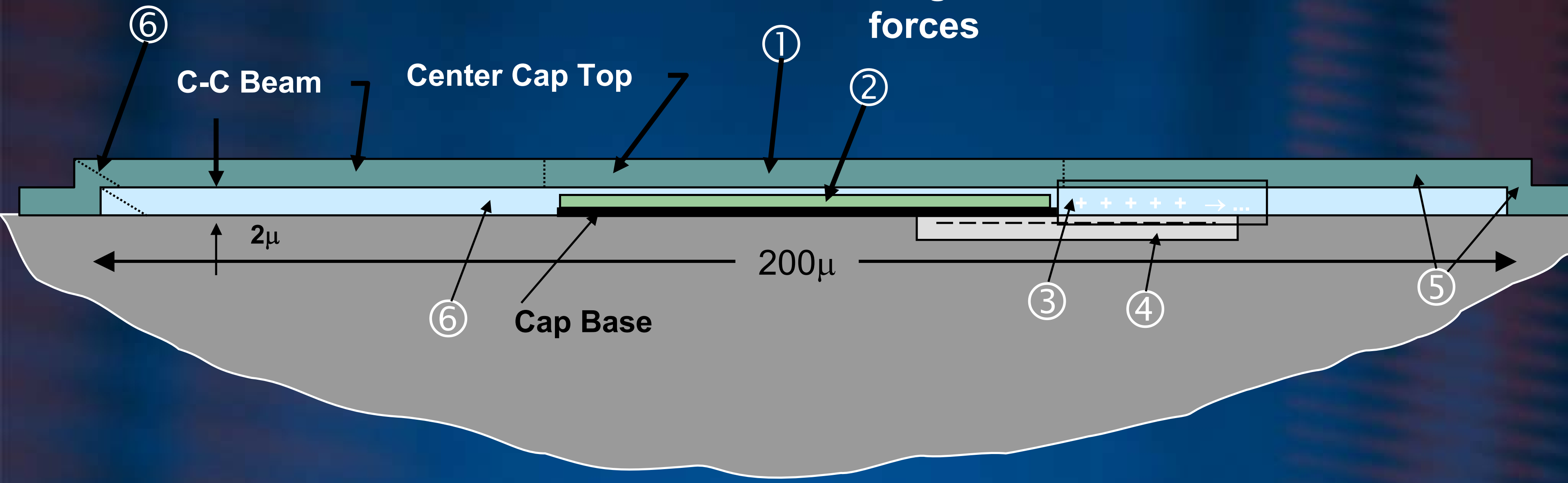
- High Capacitance shunt
- Isolation: -40 dB (3-5 GHz)
- Isolation: -30 dB (10 GHz)
- Isolation: -20 dB (20 GHz)
- Loss : -0.1 dB (10 GHz)
- (LCd Resonance effect at 3-5 GHz)
- Vp = 8-20 V
- t = N/A
- Dielectric: SrTiO3
- Cd = 50 pF





MEMS Physics is <u>Multi-Disciplinary</u>: Mechanics, Electrostatics, Fluidics, Ionics etc.

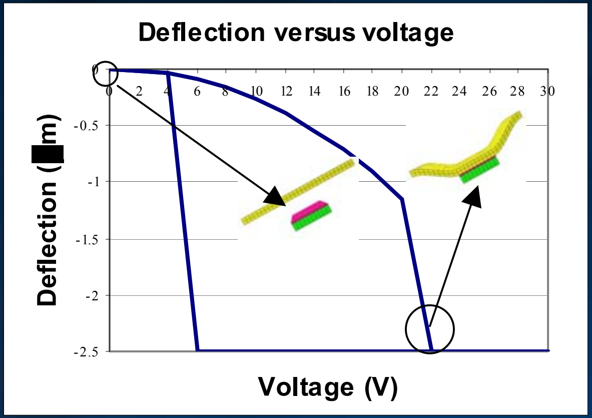
① **Stress in CC Beam**
② **Charge injection into insulator or contact erosion**
③ **Charge migration over surface**
④ **Formation of induced channel on semiconductors**
⑤ **Distributed Mass and Spring**
⑥ **Large Surface Tension formation forces**

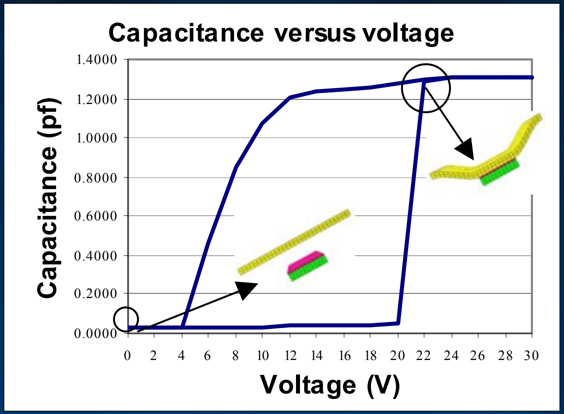


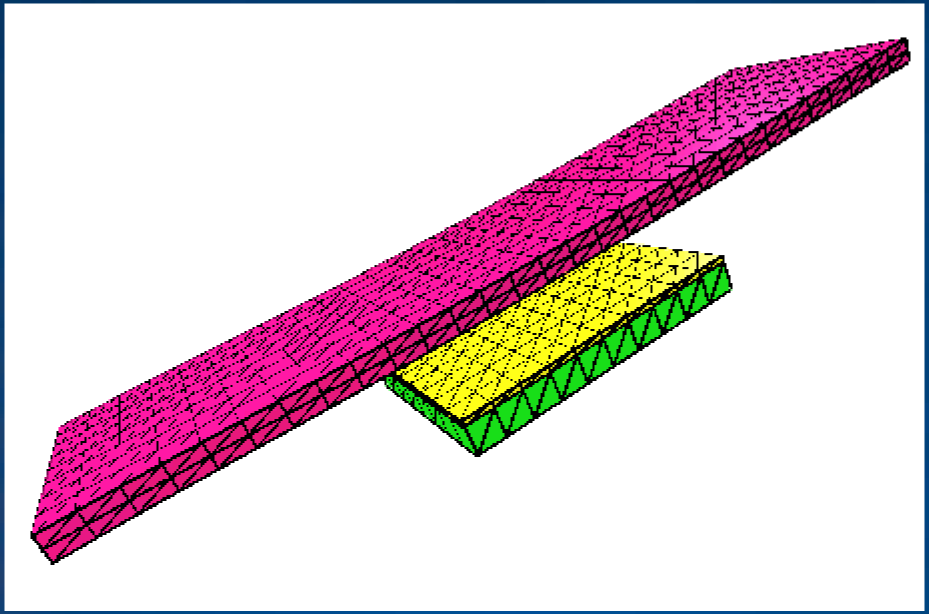
Design and Analysis of MEMS RF Switches

- Electrostatic domain
  - to solve for electrostatic pressure due to parallel surfaces.
- Mechanical domain
  - to solve for mechanical deformation, contact, stresses, heat generation etc.
- Fluidic domain
  - to solve for squeeze film dampening effect when the bridge moves.
- Electromagnetic domain
  - to solve for S, Y, Z parameters in order to obtain insertion loss, isolation and current distribution.

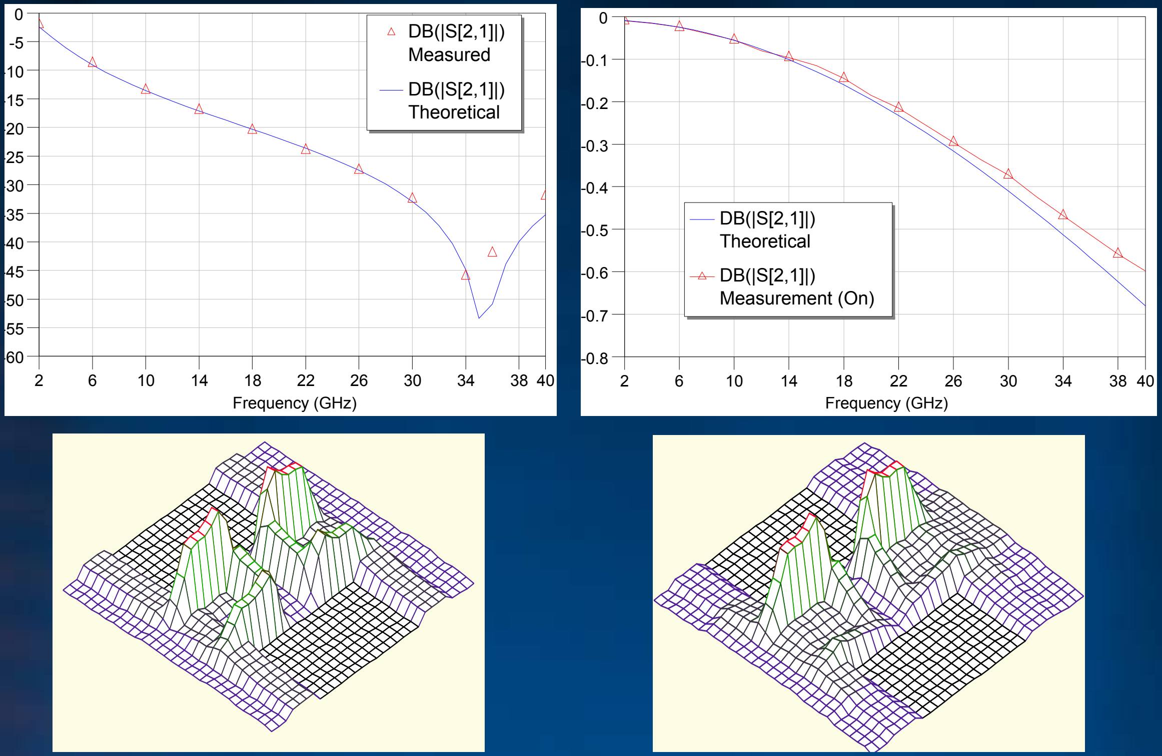
Electromechanical Analysis





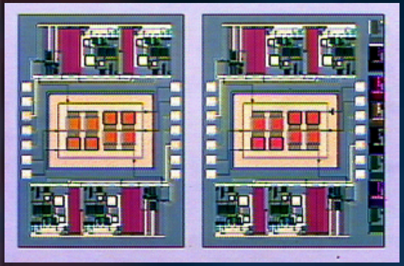
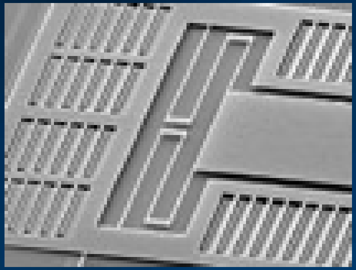
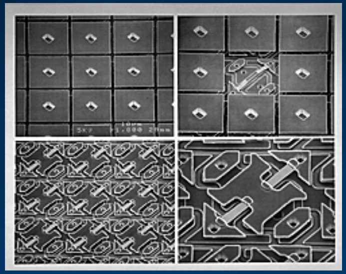
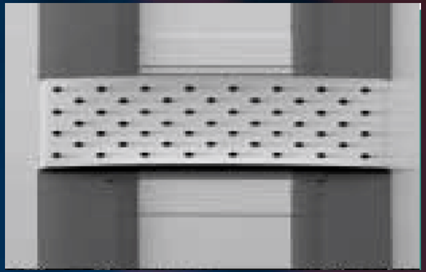


Electromagnetic Analysis



Electromagnetic (RF) analysis showing S parameters and current distribution for a capacitive switch in OFF (left) and ON (right) positions

Failure Mechanisms in MEMS Devices

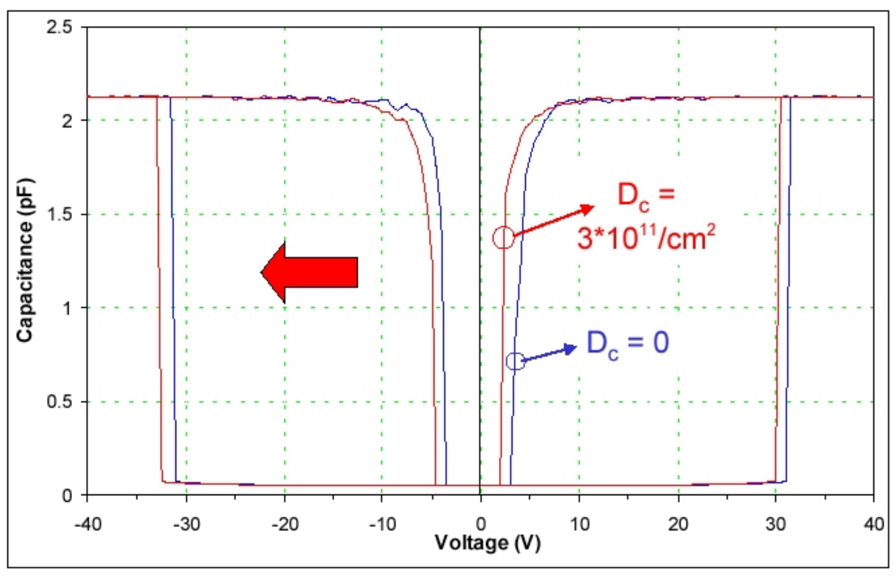
	Class I *No Moving parts*	Class II *Moving Parts, No Rubbing or Impacting Surfaces*	Class III *Moving Parts, Impacting Surfaces*	Class IV *Moving Parts, Impacting and Rubbing Surfaces*
				
Applications	*Accelerometers* *Pressure Sensors* *Ink Jet Print Heads* *Strain Gauge* *Integrated Circuits*	*Gyros* *Comb Drives* *Resonators* *Filters*	*TI DMD* *Relays* *Valves* *Pumps*	*RF Switches* *Optical Switches* *Shutters* *Scanners*
Failure Mechanisms	Particle Contamination Shock Induced Stiction	Particle Contamination Shock Induced Stiction Mechanical Fatigue	Particle Contamination Shock Induced Stiction Stiction Mechanical Fatigue Impact Damage	Particle Contamination Shock Induced Stiction Stiction Mechanical Fatigue Friction Wear

Challenges

- Lifetime and reliability
- Packaging
- Cost
- Speed

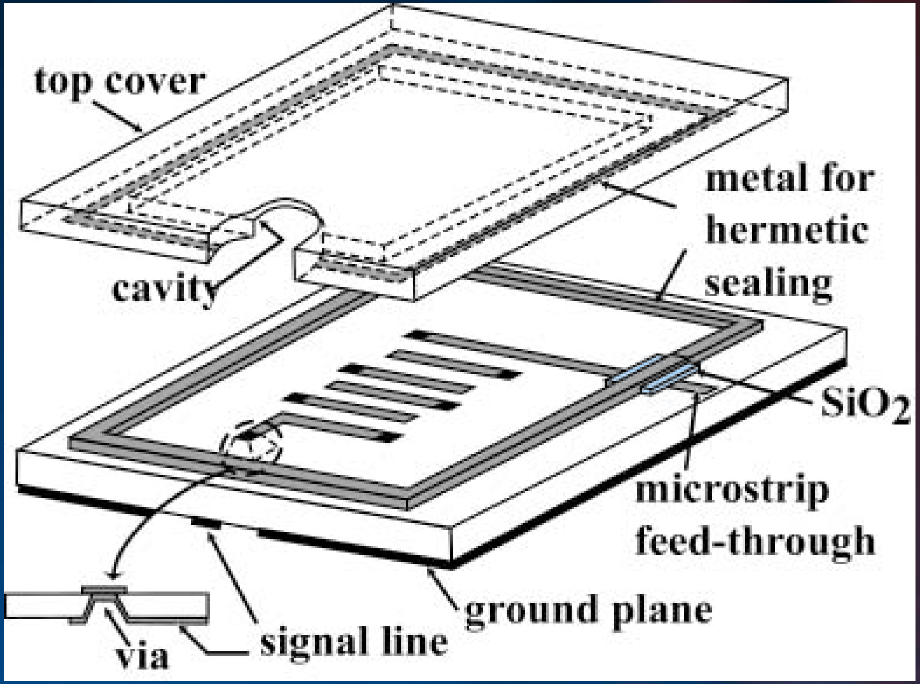
Switch Lifetimes: Capacitive Switches

- Stiction
  - Metal-to-dielectric stiction
  - Large contact area resulting in stiction due to dielectric charging
  - Water particle (water is a polar molecule)
  - Organic materials on the metal-dielectric interface
- Possible solutions
  - Package device in Nitrogen atmosphere (makes it very expensive)
  - Better design and dielectrics by reducing actuation voltage
  - Use bipolar voltage so as not to charge the dielectric (cost may be high preventing use in various portable applications)



Packaging Considerations in MEMS Circuits

- Wafer level packaging will result in lowest cost for MEMS switches.
- Packaging gas has large effect on reliability.
- Hermetic sealing is essential since MEMS switches are sensitive to humidity.
- For high performance, low quantities, packaging can be done using standard techniques.
- The highest cost will be the package in single MEMS switches. This is not the case in phase shifters or filters, or high isolation switch networks.



Conclusions

- Virtually every MEMS switch configuration is available today. The main question now is reliability and packaging.
- Reliability is currently in the 10^8 electrically, and 10^{11} mechanically.
- Failure mechanisms are:
  - Resistive failure in DC-contact switches (metallurgy, contact forces)
  - Stiction due to humidity and/or charging of the dielectric (capacitive switches)
  - Stiction due to metal-to-metal contacts (contact physics)
  - Microwelding due to large currents
- To combat failures, industry is doing the following:
  - Packaging in inert atmosphere such as Nitrogen and/or hermetic sealing
  - Large voltage and large spring constant structures
  - Development of better metal contacts
  - Designs with no contact between the pull-down electrode and the bottom metal (not applicable for current capacitive switches)

Conclusions

- Today, most MEMS switches are being developed for phase shifters and defense applications.
- Tomorrow, which is today, most MEMS switches will be developed for wireless applications and low-power applications:
  - Single-Pole Multiple-Throw Switches
  - Switched Filter Banks for portable and basestations (receive)
  - Switched Attenuators for High Dynamic Range Receivers and Instrumentation
  - Switch Matrices (Basestations and Satellite Applications)
  - Tunable Filters (High-Q Varactors)
  - Tunable Networks for Wideband Applications (Switched Capacitors, Medium Q needed)
- There are currently no high power (100 mW to 10 W) MEMS switches.
- There are currently no services or foundries for RF MEMS switches.