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RF MEMS Devices

MEMS Switch and Tunable Capacitor

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MicroElectroMechanical Systems
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Outline

- Introduction to RF MEMS
- MEMS RF Switch
  - Motivation
  - Device types
- MEMS Tunable Capacitor
  - Interdigitated vs. Parallel plate
- Device Implementation Issues
  - Reliability
  - Packaging
- Summary / Acknowledgements

MEMS for RF Communications

Leverage small mechanical motions for large RF property excursions

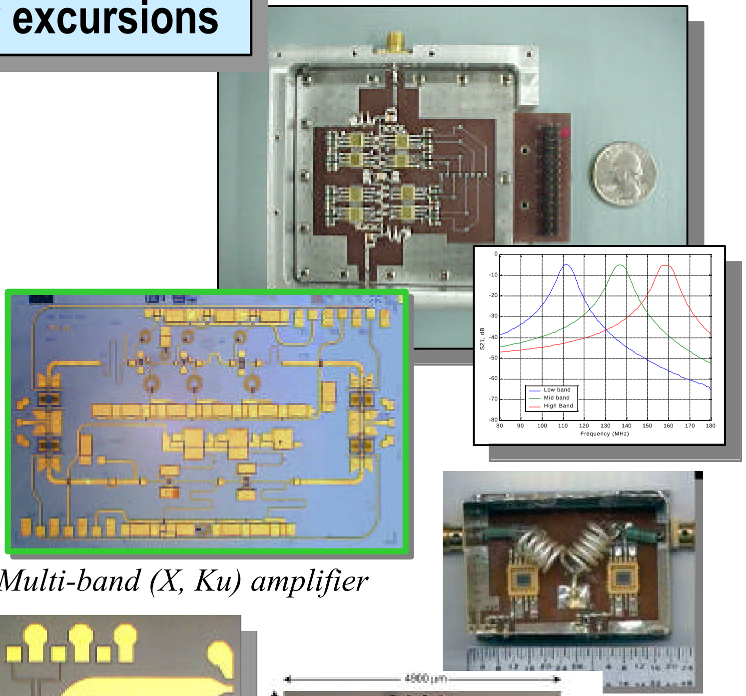
- MEMS is key enabling technology addressing pervasive trends in communications and radar systems:
  - tunability / agility / modularity / reconfigurability
  - increased functionality (component, system)
- Substantial performance improvements:
  - Insertion loss, isolation, linearity, power consumption, bandwidth, size, integration

Range of device concepts under development

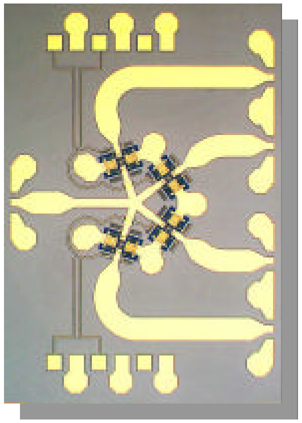
- RF Switches / Relays
- Tunable Capacitors
- Micromachined inductors
- Micromechanical resonators

⇒ Building Blocks for High-Performance Miniaturized RF Subsystems

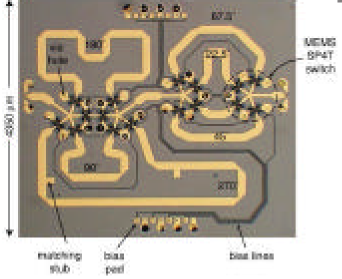
2-Pole MEMS Switched Filter



Multi-band (X, Ku) amplifier



SP4T Routing Network



X-Band Phase Shifter

Motivation For RF MEMS Switches

switching an important function in RF systems

- Significant performance advantages drive interest in RF MEMS switches:
    - Low insertion loss loss (0.1 dB up to 100 GHz)
    - High Isolation (< -30 dB up to 100 GHz)
    - Very high signal linearity (IP3> 80 dBm)
    - Very low power consumption (10-100nJ/cycle for electrostatic switch)
    - Broad application frequency (DC-120GHz)
    - Potential for low cost fabrication, integration

- However, other issues must be considered:
    - Switching time (10's μsec typical)
    - Low power handling (50-500 mW typical)
    - Packaging may be difficult and costly
    - Cycle reliability (rapidly improving)
    - Actuation voltages may be high
    - Cost and availability (still not widely available)

	PIN	MESFET	MEMS
ON-State Loss	2-4 Ohm	4-6 Ohm	0.5-2 Ohm
OFF-State Isolation	High	Medium	Very High
3rd Order Intercept	27 - 45 dBm	27 - 45 dBm	66 - 80 dBm
Size			0.2 x 0.2mm
Device Power Use	5-100mW	near zero	near zero
Control	TTL	TTL	80V

Adapted from Rebeiz, "RF MEMS", Wiley 2003

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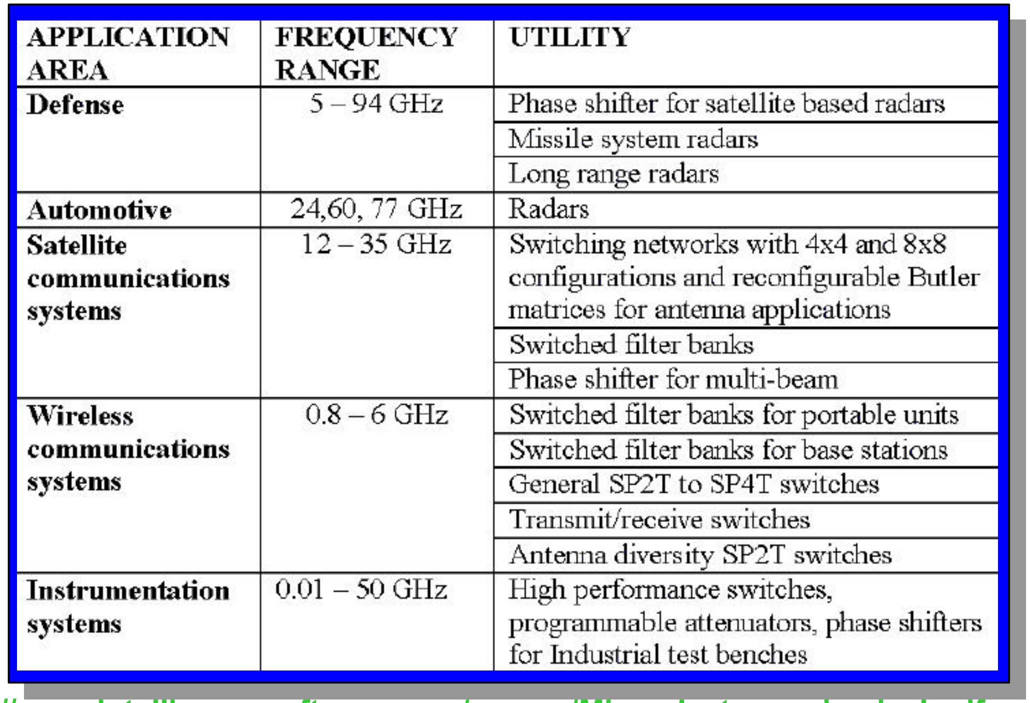
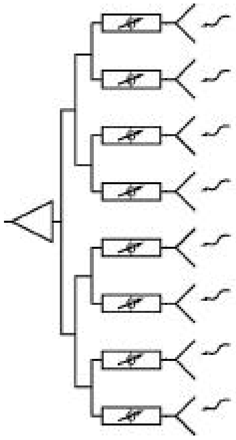
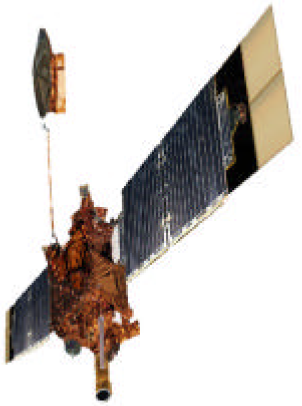
Application Areas for RF Switches

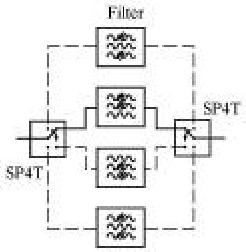


APPLICATION AREA	FREQUENCY RANGE	UTILITY
Defense	5 – 94 GHz	Phase shifter for satellite based radars
		Missile system radars
		Long range radars
Automotive	24,60, 77 GHz	Radars
Satellite communications systems	12 – 35 GHz	Switching networks with 4x4 and 8x8 configurations and reconfigurable Butler matrices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

http://www.intellisensesoftware.com/papers/Microelectromechanical.pdf





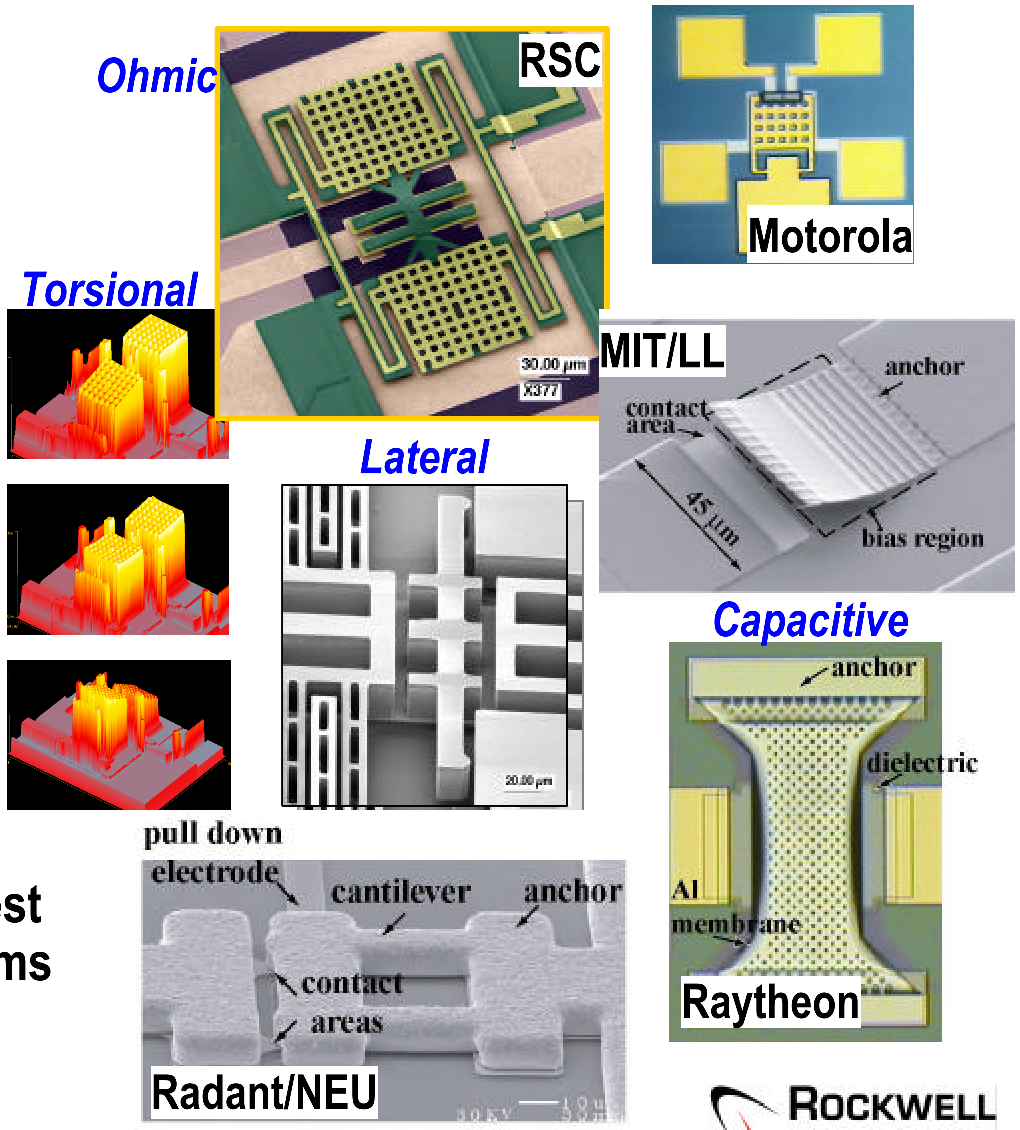


RF Switch Technologies are the critical (and enabling) technology providing for high performance, advanced capability systems of various applications:

- *Consumer Markets* – Wireless Communications, Automotive
- *Industrial Markets* – Instrumentation Systems, Satellite Communications
- *Military* – Wireless Communications, Satellite Communications, Radar

Broad Range of MEMS Switch Architectures

- **Contact Type:**
  - ohmic (metal-metal) vs capacitive (membrane)
- **Actuation Mechanism:**
  - electrostatic, thermal, magnetic, piezoelectric
- **Mechanical Construction**
  - torsional, lateral, vertical flexure
  - surface, bulk micromachining
  - Structural, contact materials
  - Isolated, non-isolated
- **RF Configuration**
  - Series vs. shunt
- **Different sensitivities to environment, test conditions, reliability-limiting mechanisms**



Ref. Rebeiz, “RF MEMS- Theory, Design, and Technology,”Wiley, 2003

Considerations for MEMS Switch Design

- Range of switch options provide huge design space for implementation
- *However…* applications requirements will typically impose significant constraints on device design options
  - *Operational requirements* (frequency, bandwidth, insertion loss, isolation, switching time, duty cycle, hot vs. cold switching, operating temperature range)
  - *Reliability considerations* (contact force, release force, sensitivity to process residuals)
  - *Implementation / Integration considerations* (drive voltage, power consumption, electronics control/integration)
  - *Environmental /packaging considerations* (environmental sensitivities, package hermeticity, package constraints)
  - *Manufacturing / cost considerations* (cost, die size, manufacturability, scalability, process robustness, yield)

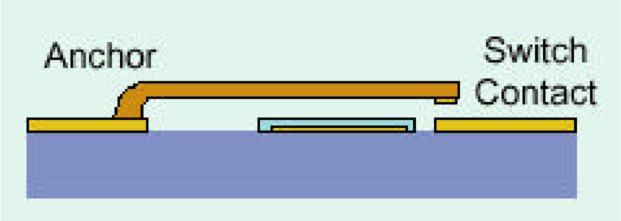
The Two Basic Types of MEMS RF Switch

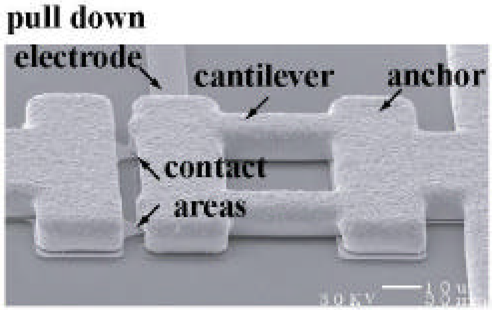
Metal-Contact Switch

- OFF state: air gap
- ON state: metal-metal contact
- Operation: DC to high frequency
- Actuation: various
- RF Configuration: series, shunt
- Pros: broadband, biasing, versatility
- Cons: power handling, high freq. isolation

Capacitive-Contact Switch

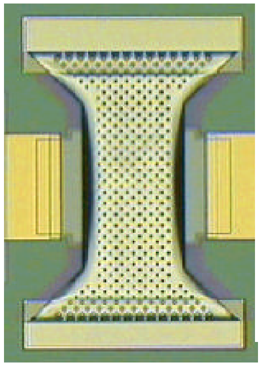
- OFF state: air gap
- ON state: metal-insulator-metal contact
- Operation: higher frequencies (>5GHz)
- Actuation: electrostatic
- RF Configuration: shunt
- Pros: power handling, no contact wear
- Cons: low freq. operation, biasing





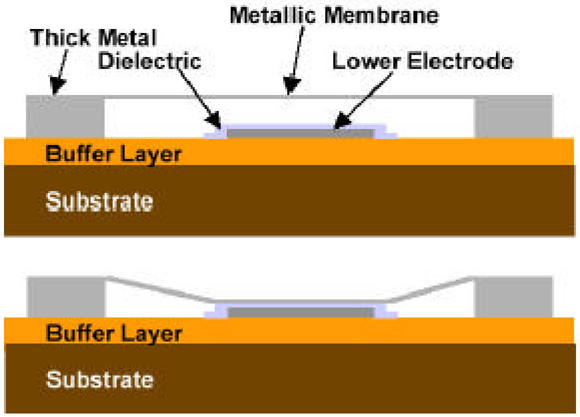
Radant Ohmic Switch

(Rebeiz, RF MEMS Theory, Design, and Technology)



Raytheon Capacitive Switch

Capacitive-Contact MEMS Switch

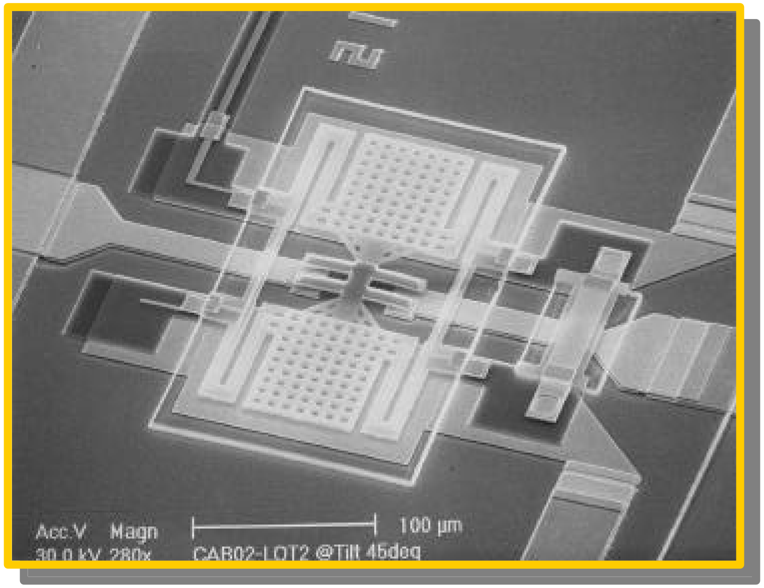


RSC MEMS RF Switch

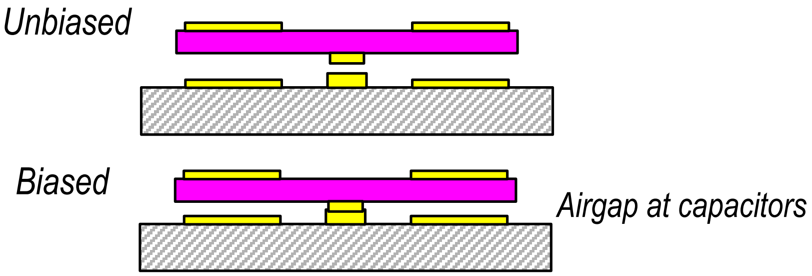
Electrostatic metal contact switch

Key Elements of RSC MEMS RF Switch

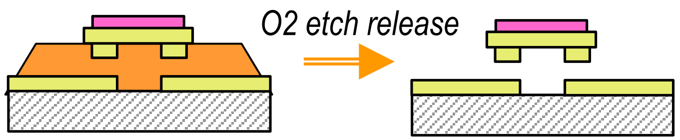
- Low-temperature processing (circuit compatible)
- Substrate independent (GaAs, Si, Quartz)
- Broadband (DC- mmWave)
- Electrostatic drive for low power consumption
- Inherent isolation between drive and signal
- Turn-on time <10ms
- Activation voltage 50-80V
- Third order intercept +80dBm



Switch Operation



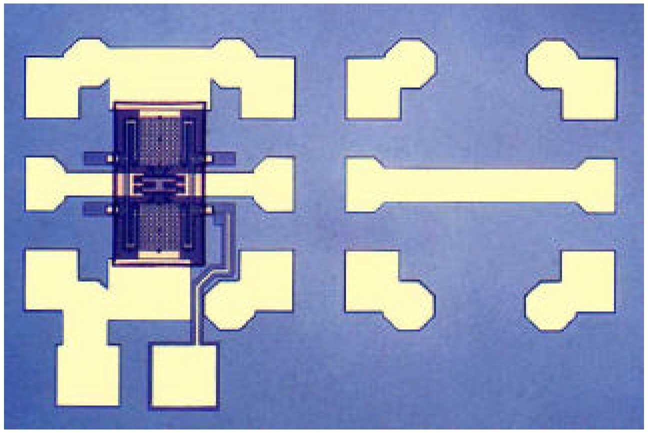
Switch Fabrication



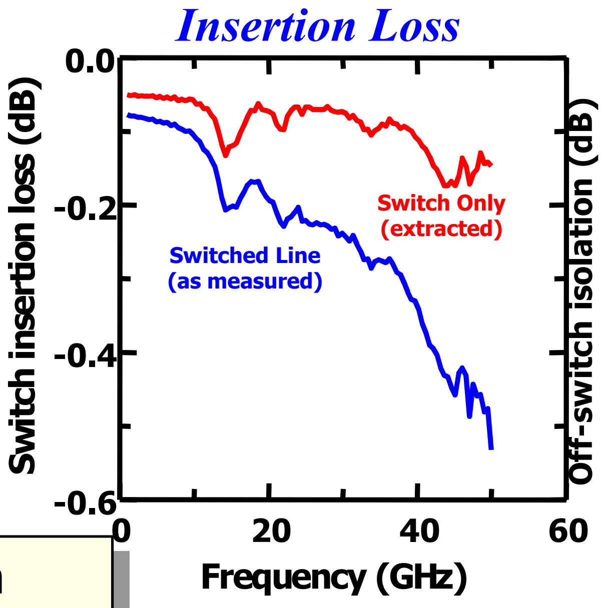
Switch built atop sacrificial platform

Etch sacrificial layer to release structure

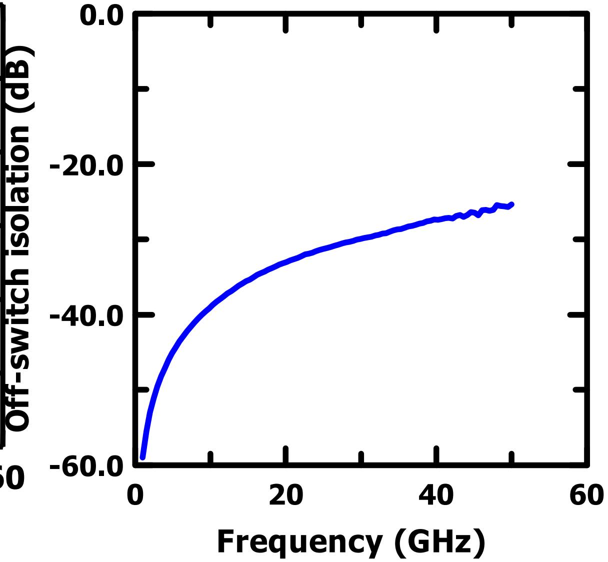
RF Performance of RSC MEMS Switch



Insertion Loss

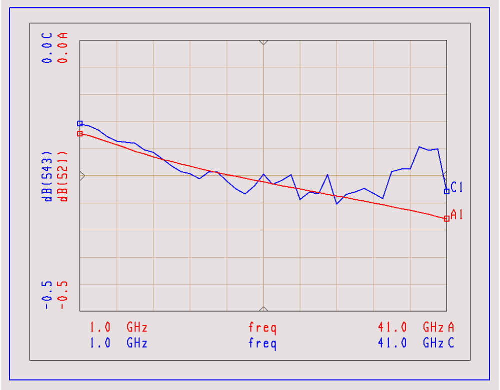


Isolation

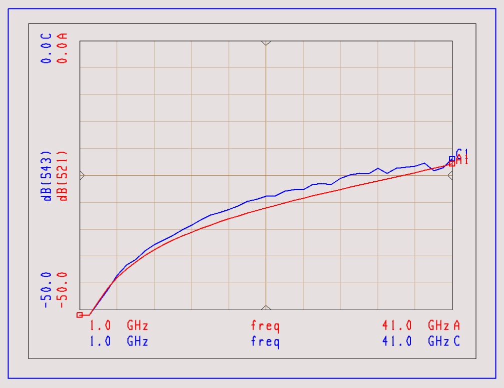


- Low Insertion loss (0.1 dB insertion loss to 40 GHz)
- Low open switch capacitance 1.75 fF
- Off-switch parasitic coupling < -30 dB up to 30 GHz
- Well-characterized RF device models

ON Insertion loss



OFF isolation



Model vs Measured S-Parameters

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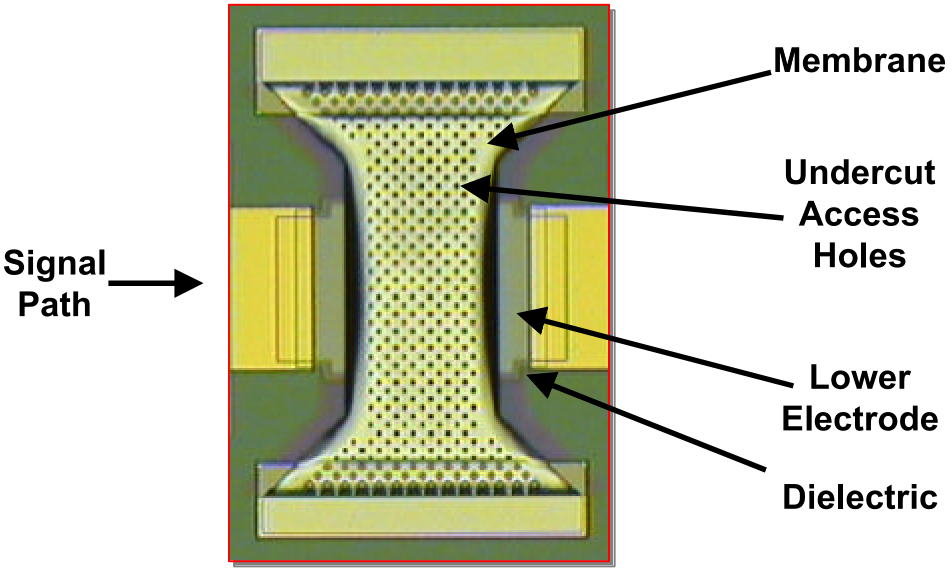
Capacitive Membrane Switches

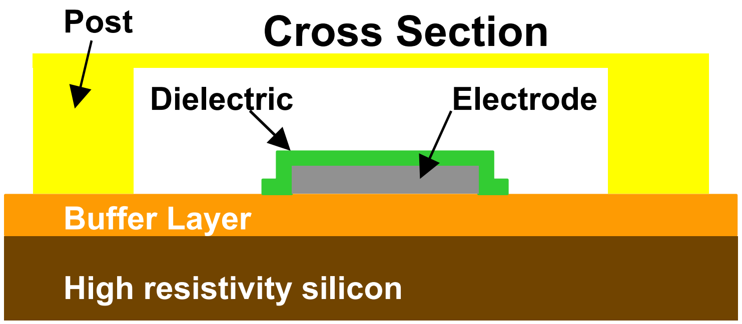
Design elements:

- Smooth surfaces, high e dielectric for maximum on-state capacitance
- Materials, mechanical designs to avoid dielectric charge trapping
- High conductivity metals for low loss at microwave, mmW frequencies

Raytheon Switch

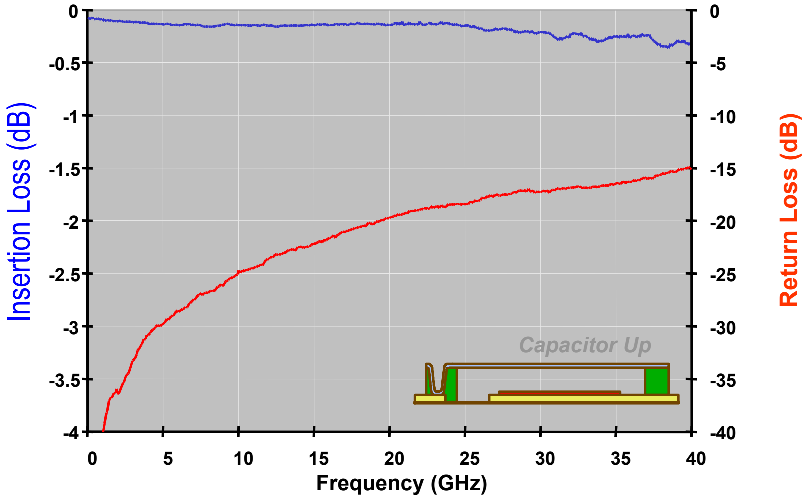


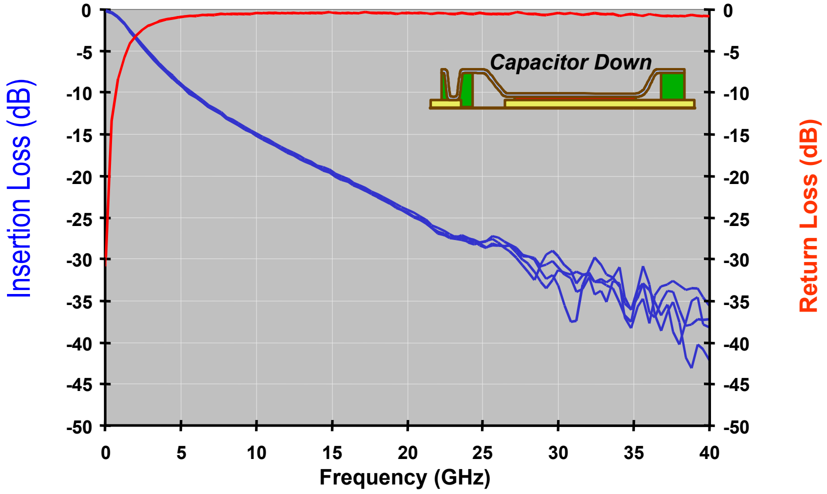
Cross Section



(Rebeiz, <u>RF MEMS Theory, Design, and Technology</u>)

Capacitive Switch Performance





Summary of Key Metrics

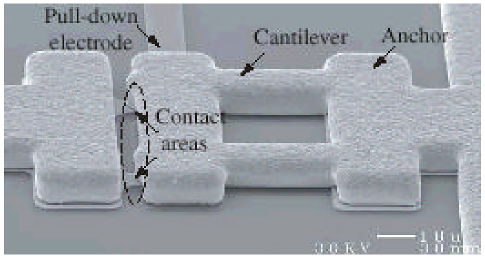
Insertion Loss @ 40 GHz	**<0.07**	**dB**
Isolation @ 40 GHz	**>35**	**dB**
Coff / Con	**.03 / 3.4**	**pF**
Capacitance Ratio	**70-110**	
Switching Speed	**< 10**	**µs**
Intercept Point	**> +66**	**dBm**
Switching Voltage	**30-50**	**volts**
Size	**280 × 170**	**µm**

Actuation a key Design Element for MEMS Switches

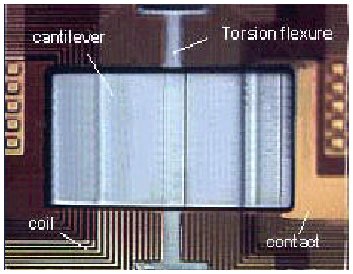
Switch properties, applications are determined largely by actuation method

Actuator Properties vs Actuation Method

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



NEU/ADI/Radant - Electrostatic



MicroLab – Electromagnetic

Electrostatic MEMS Switches

(where power, speed critical)

- defense applications
- satellite communications
- wireless communications

Thermal / Magnetic MEMS Switches

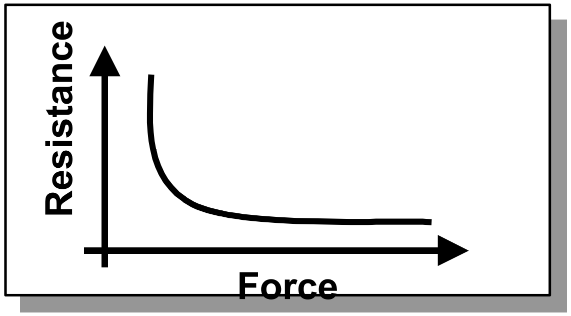
(where contact resistance, power handling at low frequency critical)

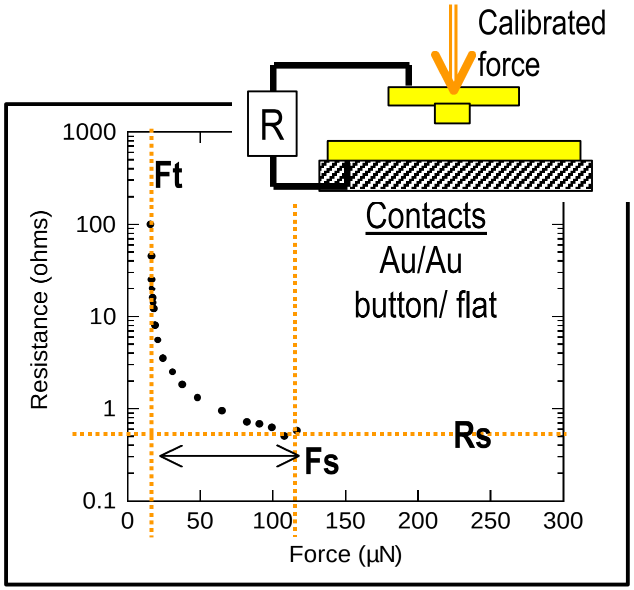
- automotive
- instrumentation systems

Need to consider contact closure / adhesion forces in actuator voltage design

Metal-Metal Contact Behavior

- Metal-metal contact requires adequate actuator force for stable resistance
  - Described by asperity contact models
- RvsF response provides valuable information on nature of contact properties
  - provides enhanced signatures of failure mechanism
- Can directly measure RvsF of MEMS switch using AFM-based force-displacement tools
  - diamond tip on high stiffness (~200N/m) cantilever
  - well-calibrated, large range force (10^{-6} - 10^{-4} N)
  - decouple actuator, contact effects
  - wafer-level probing avoids packaging artifacts
  - Non-destructive permits controlled stress testing





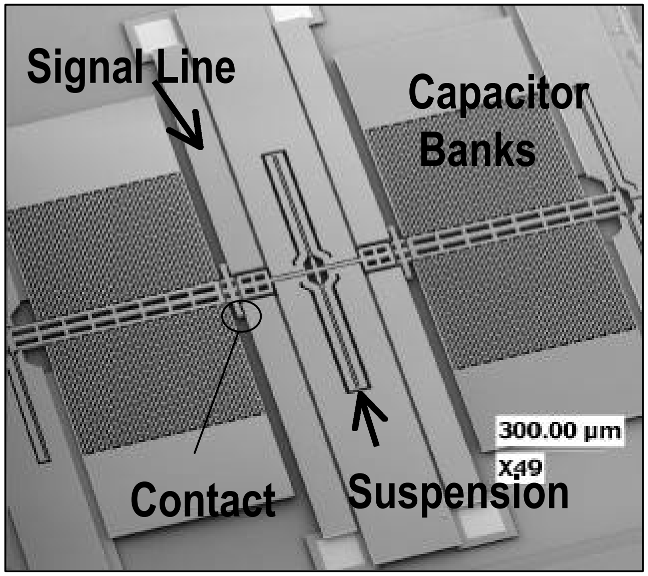
- Ft ~ 20uNt (Force to initial contact touch)
- Fs ~ 100uNt (Net force for stable resistance)
- Rs- Resistance for stable-response regime

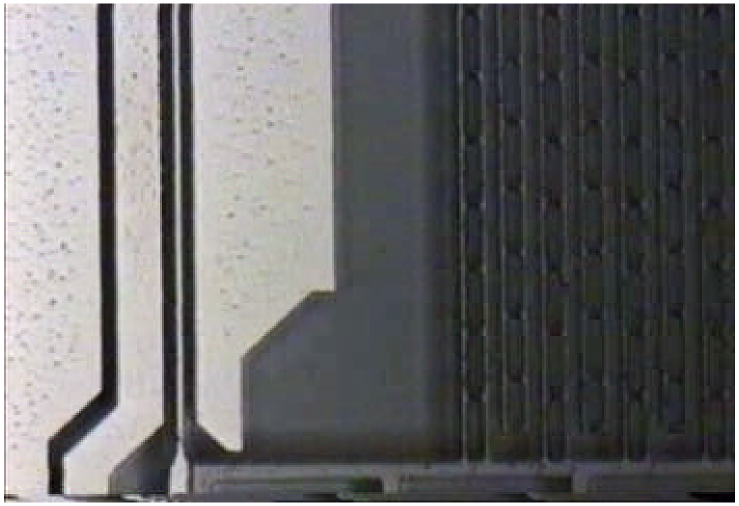
Ref: DeNatale et al., 2002 IRPS, Dallas, TX

Hybrid MEMS Switch

strategy for bypassing single-actuator constraints

- Inherent trades exist in actuator selection
  - Electrostatics attractive for low power, but require high voltage for large gap
- Hybrid actuation mechanisms attractive approach to low-power / low-voltage switch
- RSC: Demonstrate hybrid Lorentz Force / electrostatic switch
  - Short-duration Lorentz force to close gap, electrostatics to hold
- Characteristics:
  - Low voltage (1-20V)
  - Active open (bi-directional, 50-300mN)
    - Robust against stiction
  - Double-throw operation
  - Low Power Consumption (10-500nJ/cycle)
- Hybrid Thermal/Electrostatic actuation also demonstrated (Saias, Transducers '03)

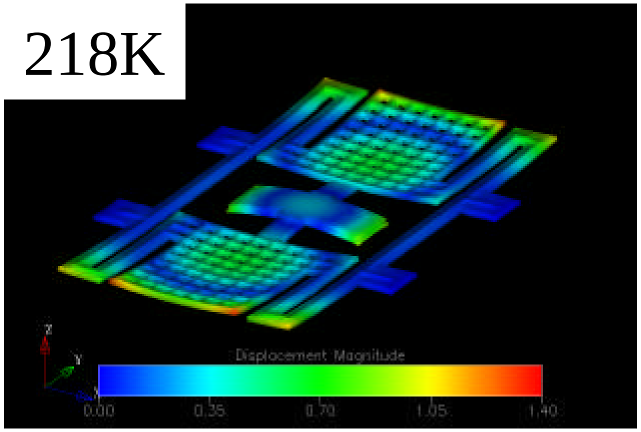




Borwick et al., Transducers '03

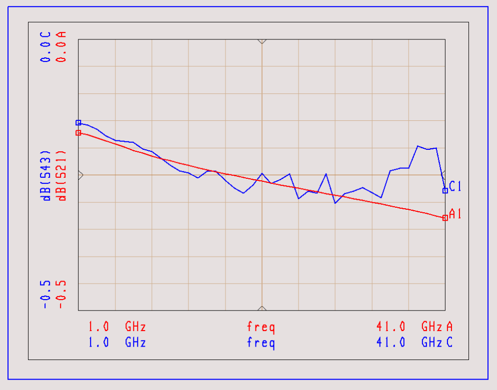
Switch Modeling Requires Multi-Physics Approach

Thermomechanical Modeling

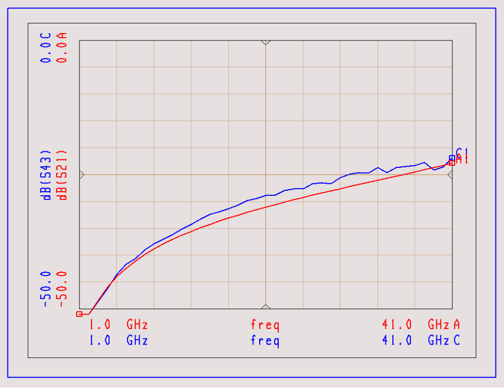


RF Modeling

ON Insertion loss

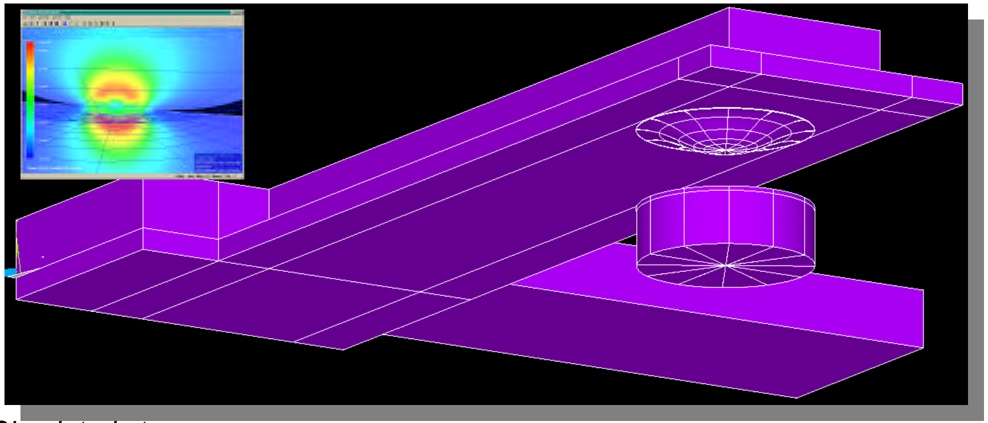


OFF isolation



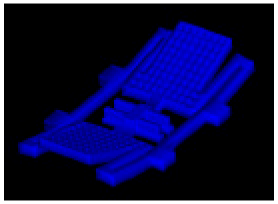
Simulated (red) and measured (blue) S-parameter data for MEM switches

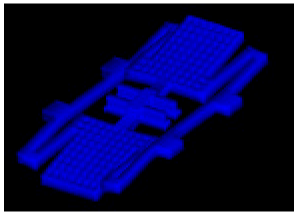
Dynamic Impact Modeling

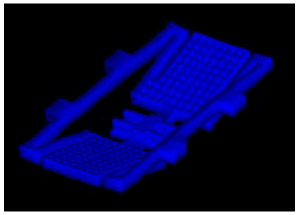


Simulated stress distribution in switch contact (elastic model)

Dynamic Modal Analysis







Multi-Physics Modeling Required

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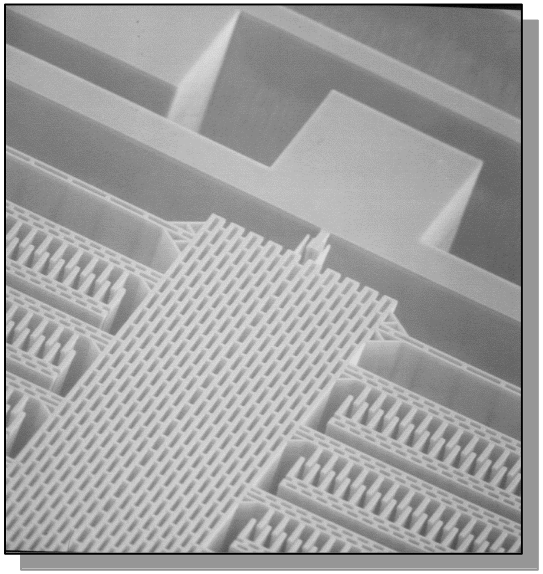
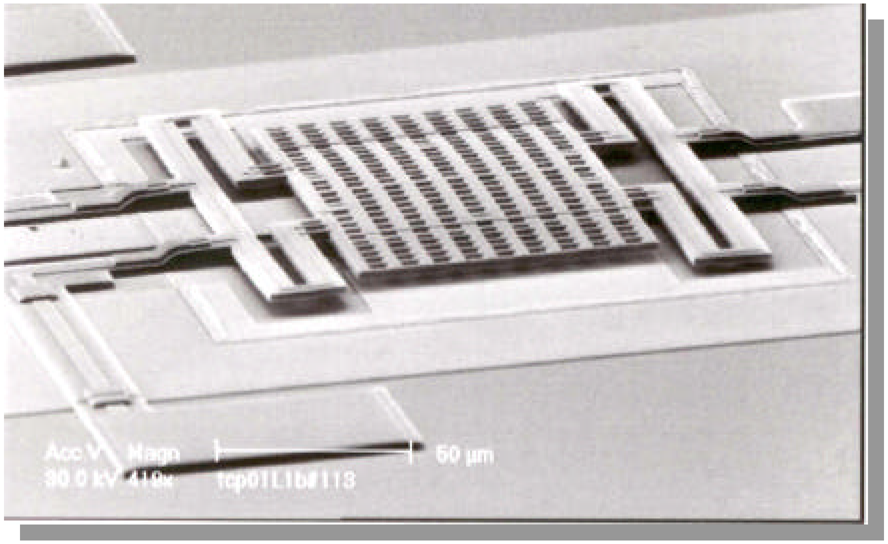
MEMS Tunable Capacitors

- Mechanically control gap or overlap area of capacitor plates
  - Parallel plate (gap tuned)
  - Interdigitated (area tuned)
- Key metrics: Tuning range, Q, base capacitance, tuning speed, vibration/acoustic sensitivity, linearity



Interdigitated

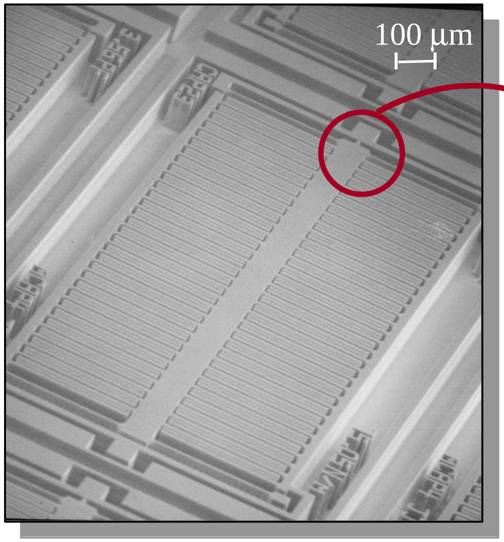
- Bulk, surface micromachining
- Wide tuning range

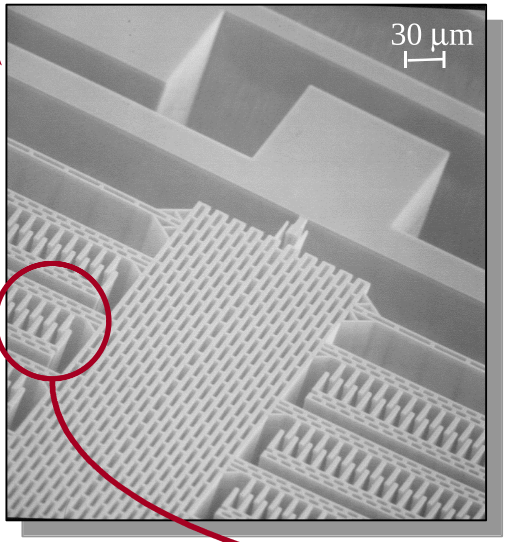


Parallel Plate

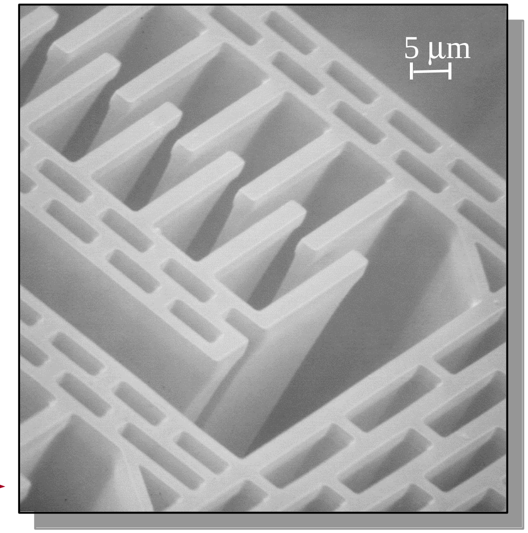
- surface micromachining
- Small area, high Q

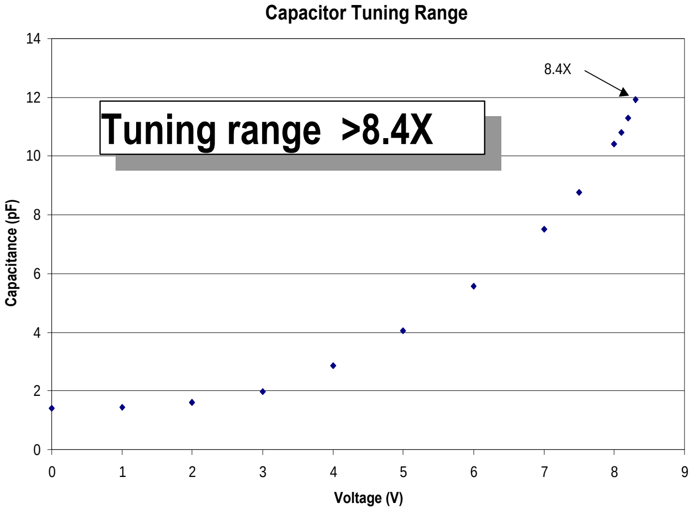
RSC MEMS Tunable Capacitor (Varactor)





SEM micrographs showing the high aspect ratio feature of the MEMS tunable cap.

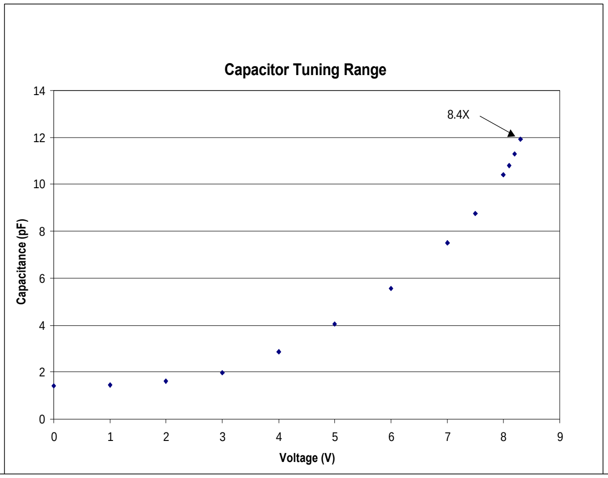




Tuning range: >8:1
Base capacitance: 1.5 - 2pF
Electrical Q: 30-150
Max tuning voltage: 6-40V
Mechanical Resonance : 0.4 - 12kHz typ.
Electrical self-resonance: 6GHz

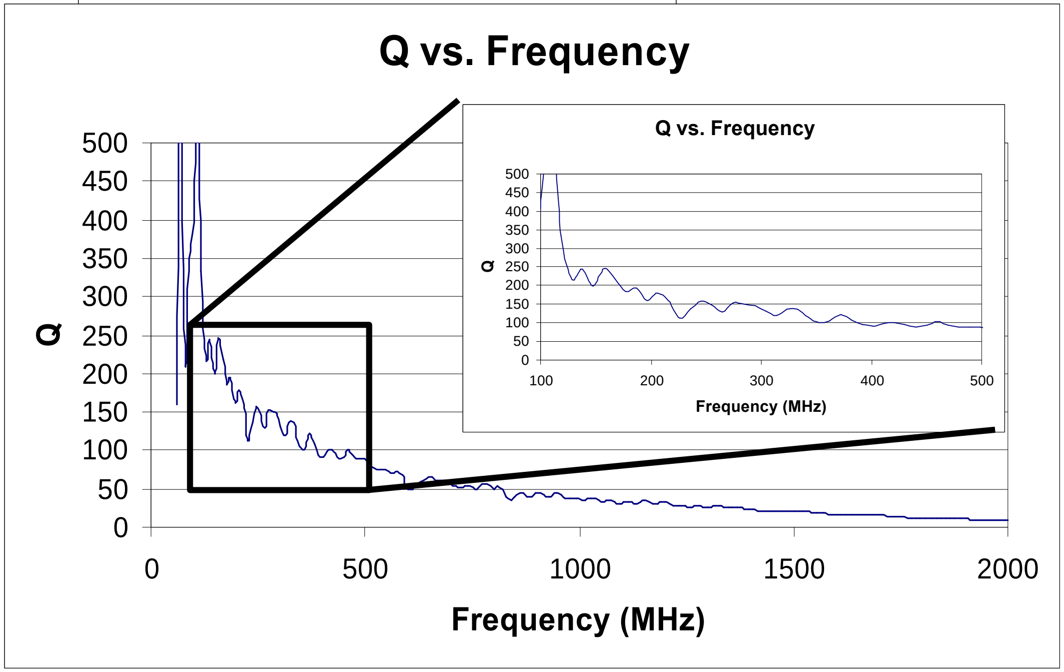
Rockwell Scientific

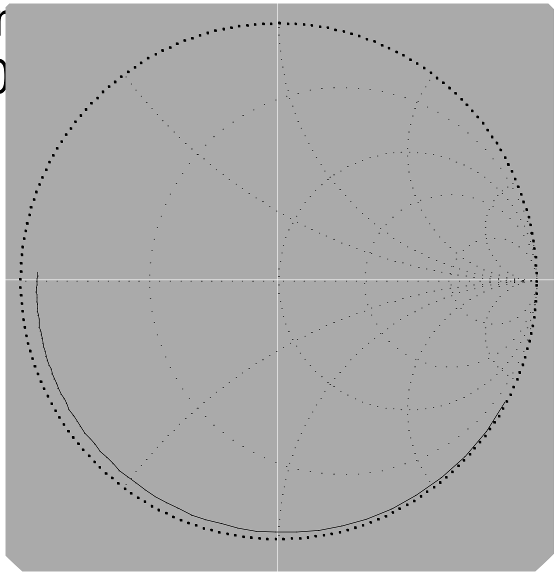
RSC MEMS Tunable Capacitor Specifications



Parameter Ranges:

- Tuning Range: 1.5 - 12 pf. (8.4x)
- Resonant Frequency: 0.5 – 12kHz
- Actuation voltage: 6 - 40 Volts
- Series Resistance:1 - 2 Ohr
- Q at 1.5 pf: Above 100 (<80



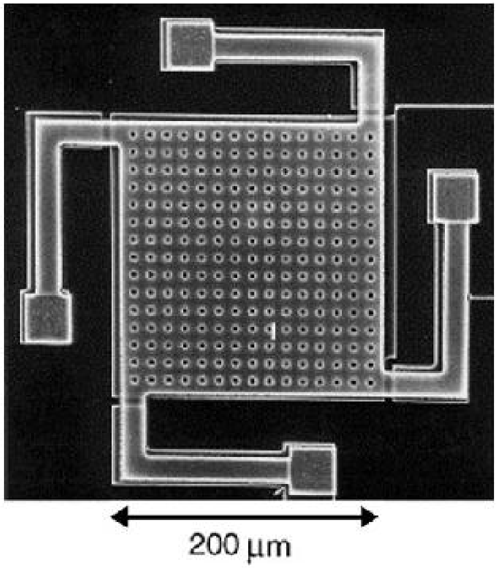


Tuning range of >8.4X over *Application-Relevant* capacitance values

MEMS Tunable Capacitors

parallel plate (gap tuned) devices

- Conventional parallel plate capacitors widely implemented using surface micromachining processes
  - Typical ~0.5-2.0pF base, Q ~ 23-60 (1GHz)
- Theoretical maximum capacitance tuning range of parallel plate =50% due to electrostatic instability (typically 15-40%)
- Surface micromachined device offers advantages for integration, high frequency operation



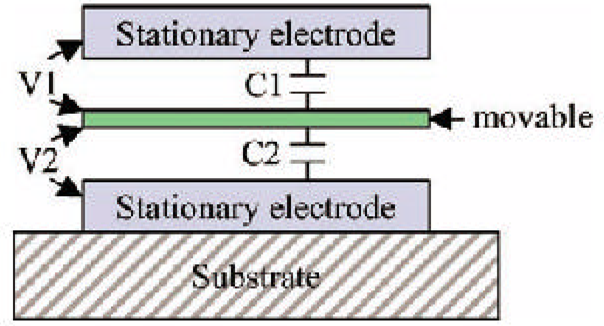
D.J. Young and B.E. Boser, 1996 Solid State Sensor and Actuator Workshop. Taken from Yao, 2000

Extended Range Tunable Capacitors

approaches to mitigate 50% tuning limit

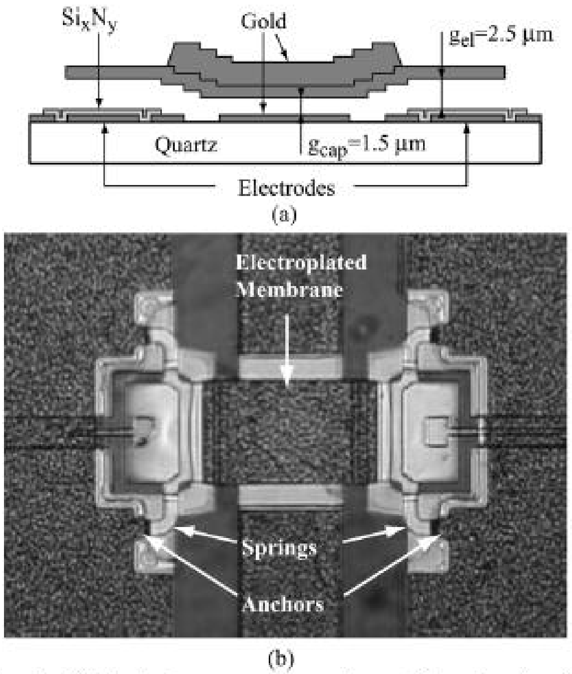
- Extended tuning devices extend parallel plate range (differential gap, dual drive)
- Predict theoretical tuning range of >100%
  - 100% tuning demonstrated

Dual Drive (Balanced) Tunable Capacitor



From Yao, J. Micromech. Microeng., 2000

Differential Gap Tunable Capacitor

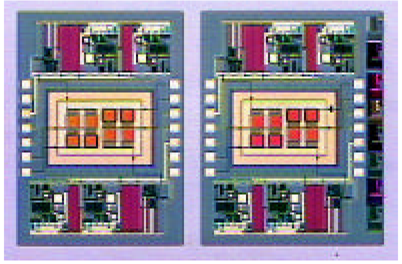
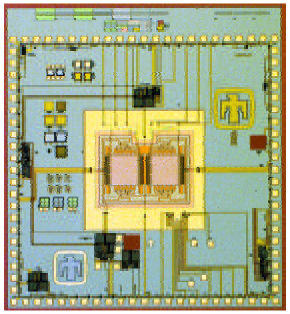
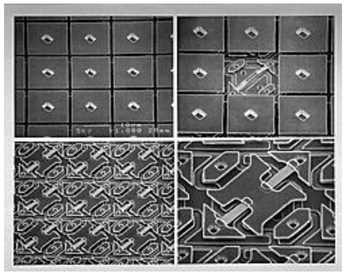


Dussopt and Rebeiz, IEEE MTT-S, June 2002

Key Issues in RF MEMS Insertion

- **Reliability –**
  - Switch contact reliability under many-cycle operation a key hurdle in widespread application, but rapidly improving
    - Up to 100 Billion cycles demonstrated
  - Very dependent on operating environment / condition
- **Packaging-**
  - Cost, RF performance, reliability all strongly impacted by packaging approach
  - Wafer-scale hermetic encapsulation attractive avenue
- **Power Handling –**
  - Small contact areas for ohmic switch (= high power density) ultimately limit operation under elevated signal powers

MEMS Reliability Taxonomy

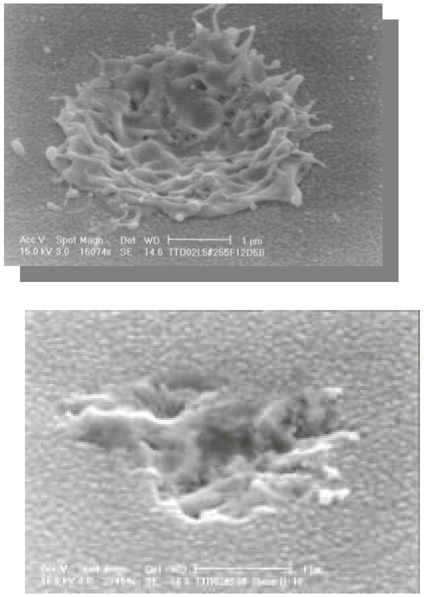
Class I	Class II	Class III	Class IV
No Moving parts	*Moving parts;* *No rubbing or impacting surfaces*	*Moving parts;* *Impacting surfaces*	*Moving parts;* *Impacting and rubbing surfaces*
			
Pressure Sensors **Ink Jet Print Heads** **Strain Gauge**	**Gyros, accelerometers** **Comb Drives** **Resonators** **Tunable Capacitors**	**TI DMD** **Valves** **Pumps** **Switches/Relays**	**Optical Switches** **Shutters / Scanners** **Locks** **Switches/Relays**

Recommend separate category for switches (Class III/IVb), since not only contacting, but *functionality depends on nature of contact*

Sources :MANCEF International Roadmap 2002
Sandia National Laboratory Reliability Short Course

Issues in MEMS Switch Reliability

- Low force operation (*typically* 10’s - 100’s mN)
  - sensitive to adhesion effects, interposed films, electro-mechanical influences
- Highly surface dominated geometry
- Inherently multi- physics system:
  - *mechanical* (movable structure)
    - statics, dynamics, gas interactions, tribology, fatigue, stress
  - *electrical* (actuator)
    - charge trapping, field-induced transport
  - *chemical* (contact surfaces)
    - contact materials, surface films (envt, process)
  - *thermal* (resistive heating of contacts)
  - *physical* (contact topology, materials)

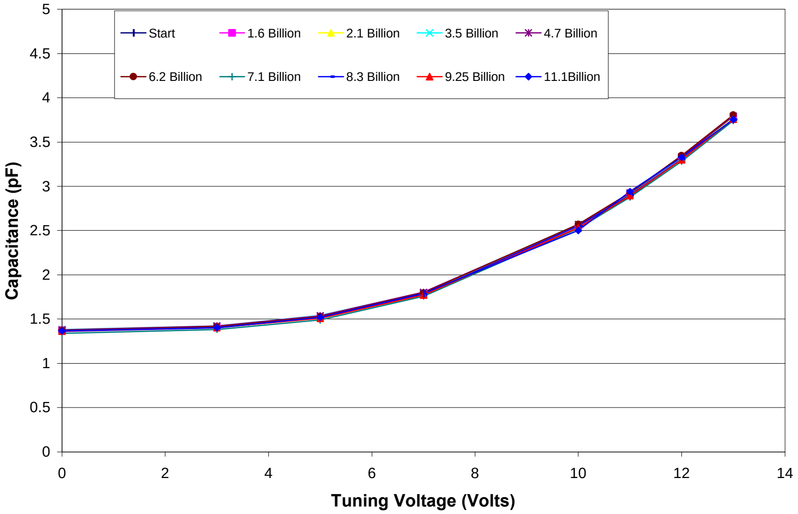


Contact damage morphologies

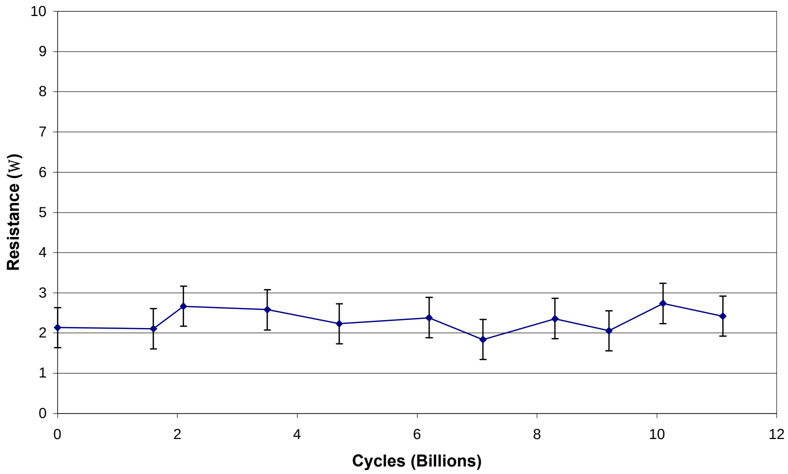
Despite inherent challenges, demonstrations of high cycle lifetimes ($1x10^{11}$) achieved

RF MEMS Reliability – Tunable Capacitor

- Tunable Capacitor device favorable construction for high-reliability
  - Non-contacting (stiction, surface degradation resistance)
  - Single xstal Si structural material (fatigue resistance)
- Devices subjected to large numbers of cycles without apparent degradation
  - Mechanical cycling to 65B cycles with no change in resonant frequency
  - Electrical testing to 10B cycles with no change in CvsV characteristics

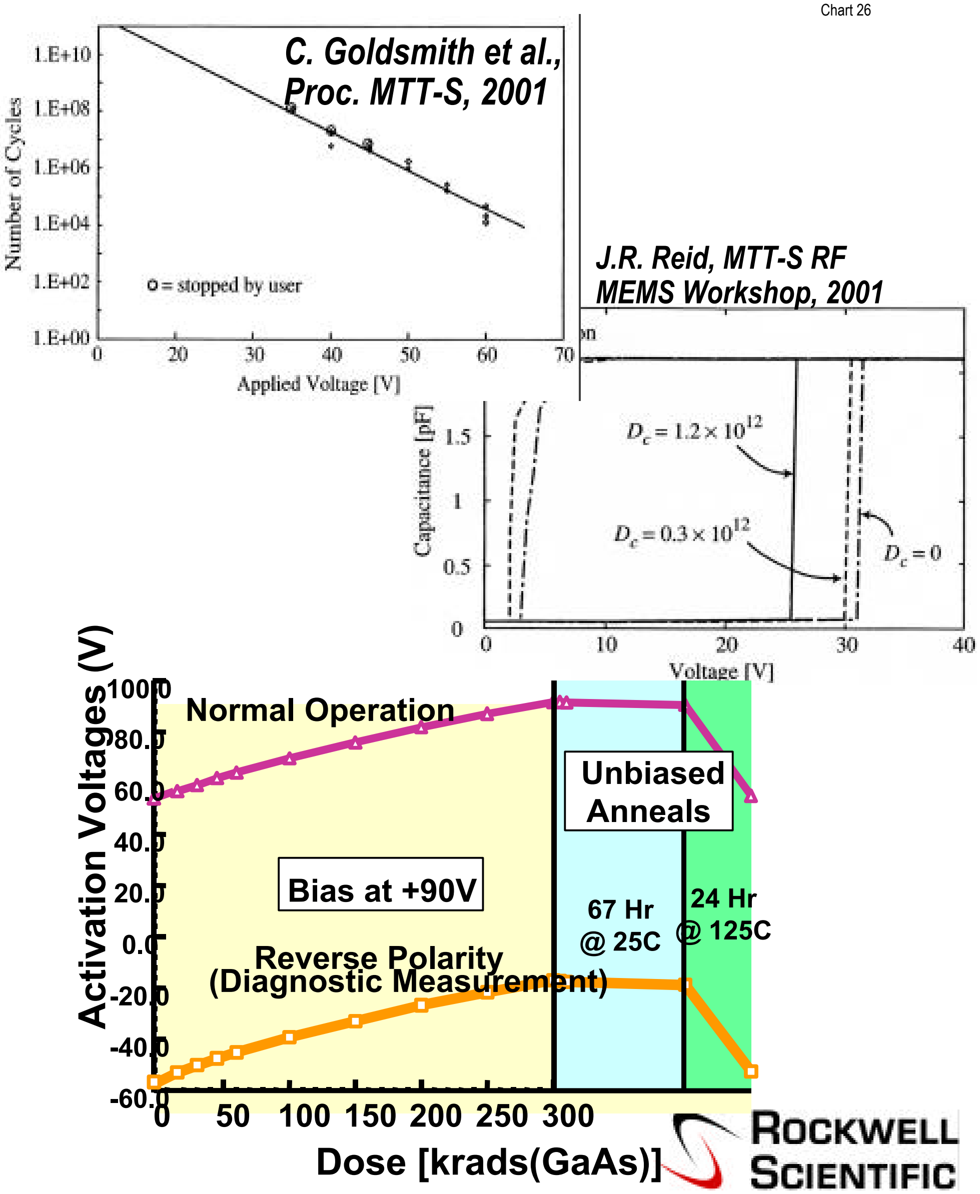


Series Resistance Change Over Lifetime



Dielectric Charge Trapping Effects

- **Use of dielectric materials in electrostatic actuators can lead to dielectric charge trapping**
  - Self-generation through actuator fields
  - Introduced by ionizing radiation
- **Very significant in capacitive switch devices due to high e-fields**
  - Lesser impact on ohmic switches
  - larger separations reduce field
- **Effect may be significant for space applications**
  - S. McClure et al., Proc. NSREC 2002
- **Mitigation through drive waveform, actuator design, material selection**

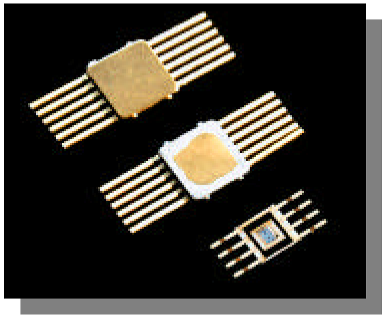


C. Goldsmith et al., Proc. MTT-S, 2001

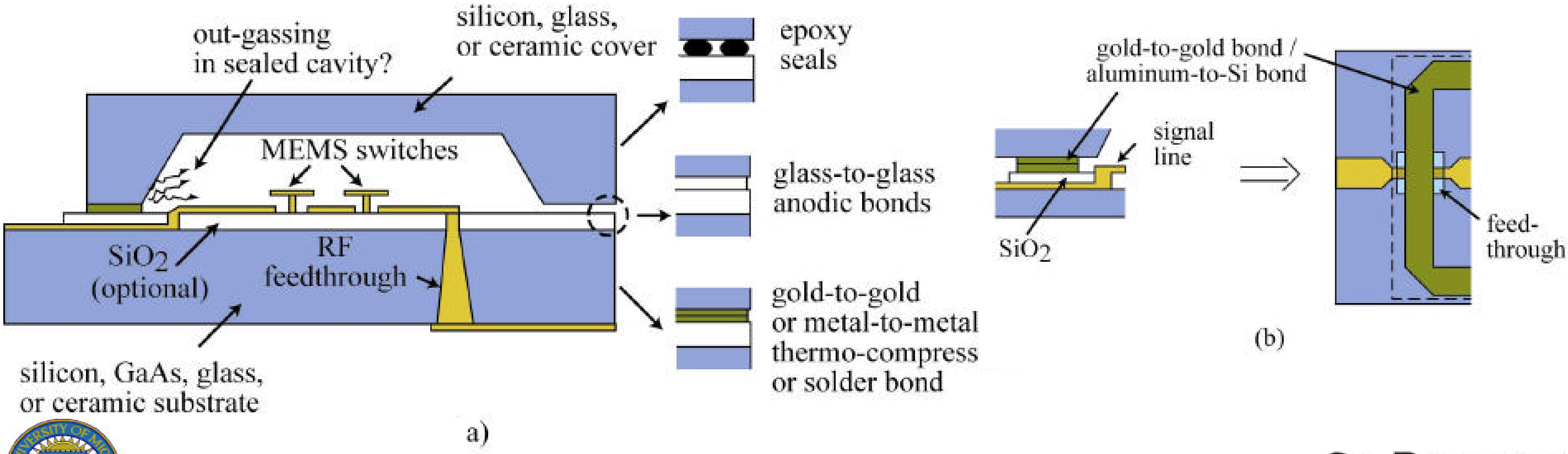
J.R. Reid, MTT-S RF MEMS Workshop, 2001

RF MEMS Packaging

- Packaging can have significant impact on reliability, cost, performance
  - Humidity related stiction, environmental surface reactants
  - RF transitions require careful design
- Wafer-scale package concepts offer low-cost, high-performance solution



Packaged MEM Switches with metal and glass lids



Summary and Conclusions

- RF MEMS an enabling technology for high-performance communications / radar systems.
- RF switch highly attractive for electrical characteristic
  - low loss, high isolation, high linearity, wide band, low power, integration compatible
  - Wide range of electrical / mechanical design elements must be considered in optimal component development
  - Development efforts making steady progress in reliability, packaging, integration
- MEMS tunable capacitor enables wide tuning range operation
  - Wide tuning range, improved signal linearity provide reduced parts count
  - Present efforts targeting improved tuning speed, damping, Q

Selected References

THE Reference Text in the RF MEMS field:

•Gabriel M. Rebeiz, 2003 “RF MEMS Theory, Design, and Technology”(John Wiley & Sons, Hoboken, NJ).

Selected publication surveys of RF MEMS

- “Topical review: RF MEMS from a device perspective,” J.J. Yao, *J. Of Micromechanics and Microengineering*, Vol. 10, 2000, pp. R9-R3
- “MEMS for wireless communications: ‘from RF-MEMS components to RF-MEMS-SiP’”, H.A.C. Tilmans, W.De Raedt and E. Beyne, *J. Of Micromechanics and Microengineering*, Vol. 13, 2003, pp. S139-S163; H.A.C. Tilmans, Eurosensors XVI

Selected on-line surveys of RF MEMS:

•**http://www.intellisensesoftware.com/papers/Microelectromechanical.pdf**

Selected publications on the RSC MEMS Switch:

- “MEM relay for reconfigurable RF circuits,” R.E. Mihailovich, M. Kim, J.B. Hacker, E.A. Sovero, J. Studer, J.A. Higgins, and J.F. DeNatale, *IEEE Microwave Wireless Components Lett*., vol. 11, pp. 53-55, Feb 2001
- “Low-Loss 2- and 4-Bit TTD MEMS Phase Shifters Based on SP4T Switches,” G.L. Tan, R.E. Mihailovich, J.B. Hacker, J.F. DeNatale, and G.M Rebeiz, *IEEE MTT-S Special Issue on RF MEMS*, January 2003.

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