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RF FPGA Annual Review:
Programmable RF Acoustic Filter Elements

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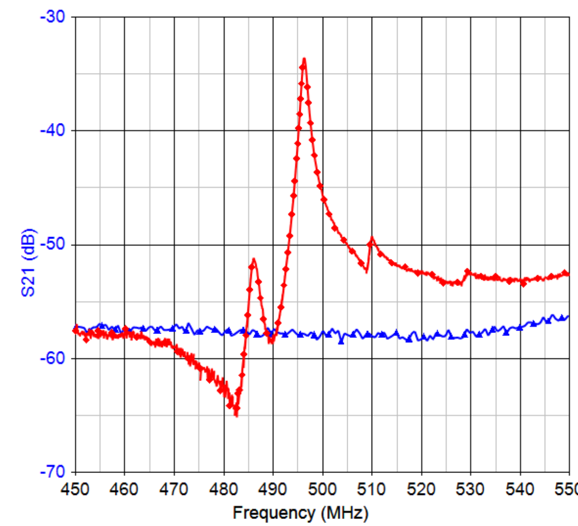
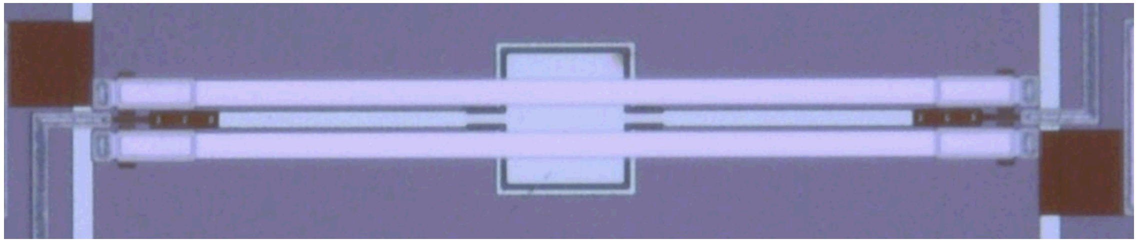
Overview

- **Project Objective: Demonstrate tuning and reconfigurability of high-Q resonators and filters using MEMS-switch based fingers.**
  - Designed project around demonstrating switch tuning; de-emphasized fixed filters
- **Current Status: Demonstrated on/off switching of piezoelectric filters using MEMS switches; many filter designs currently in fabrication.**
- **Outline**
  - Overview and Value Proposition
  - Technical Approach and Summary of Achievements
  - On / Off Resonator Concept
  - MEMS Switch Results
  - Resonator and Filter Modeling
  - Filter Design Concepts
  - Paths to Improved Performance
  - Assessment and Prospects





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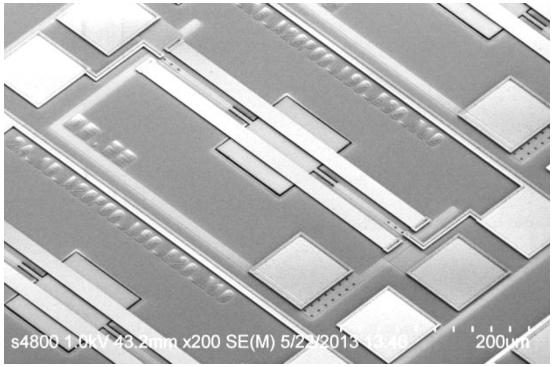
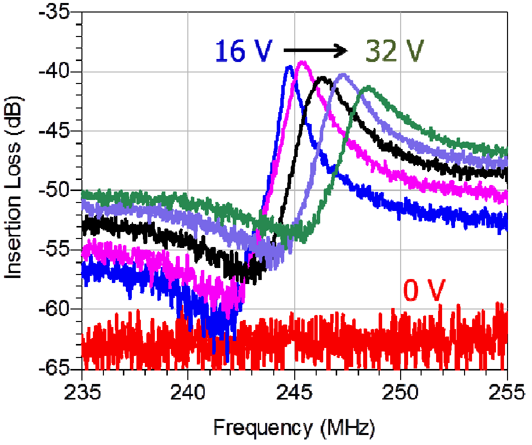
Project Goals

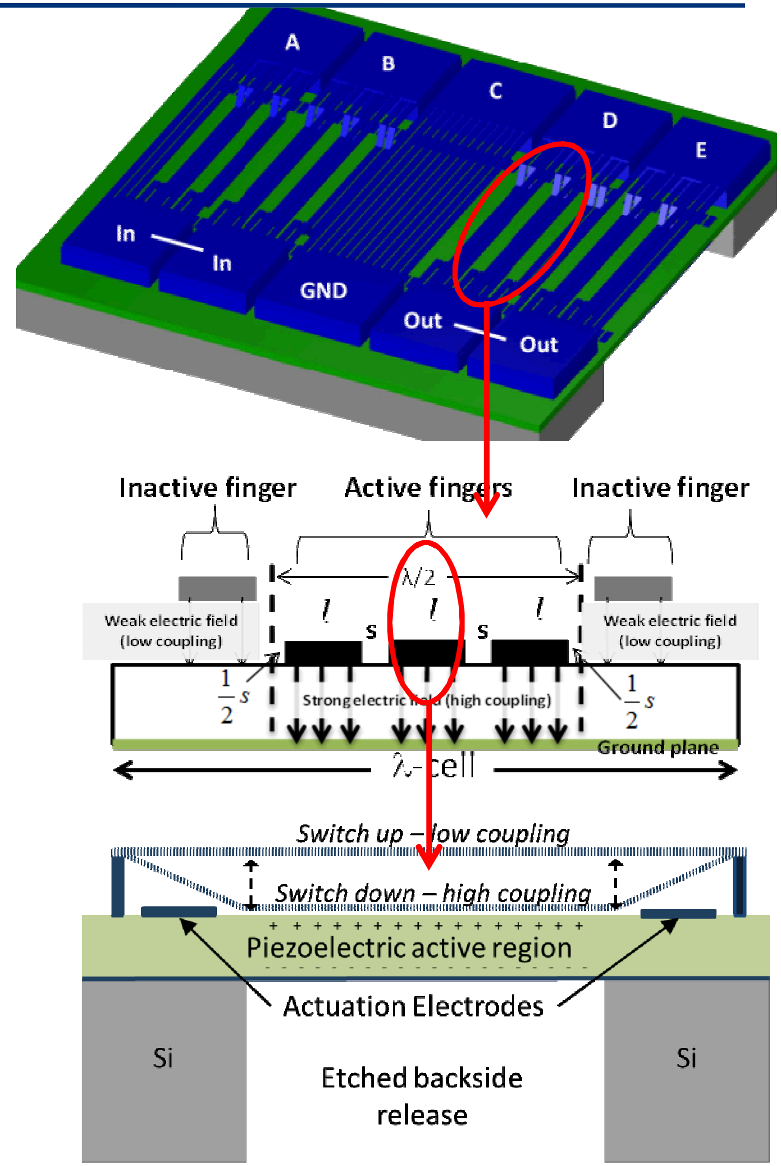
- **Description: Fundamental research activity with goal of advanced technology demo and eventually transition.**
- **Thesis Statement: MEMS switches can modulate electrical coupling of piezoelectric resonators with negligible degradation, enable high-Q switched and reconfigurable filters, and achieve performance currently unobtainable with fixed acoustic resonator filters and/or tunable electromagnetic filters.**
- **Technical Goals:**
  - Stage I: demonstrate and provide assessment of switched resonator tuning
  - Stage II: demonstrate five-state high-Q tunable filter
  - Stage III: demonstrate five-state high-Q tunable filter with packaging and control





Value to the DARPA Mission

- **Maintain the technological superiority of the U. S. military**
  - If successful, this approach will enable switched and tunable filters that are an order of magnitude smaller than existing solutions in the kHz to low GHz range.
  - This will introduce new application- and standard- agility, and enhance the performance of future RF systems, and reduce supply chain complexity.
- **Prevent technological surprise**
  - Early investigation into this tunable filter approach provides insight and understanding into the capabilities and challenges of this technology.
- **Revolutionary, High-Payoff Research**
  - As this is the first time that this approach has been attempted, this research is revolutionary; if successful, it has the potential to revolutionize government and commercial RF front ends.
- **Bridging the gap between fundamental discoveries and use**
  - Maturation and transition of this fundamental research will provide a unique capability to the U. S. military and provide the first tunable, high-Q, filter technology.



Review of Technical Approach

- **Concept: Acoustic filter with multiple segments (five shown in figure)**
  - Blocks on end can be transducer or reflector (A,E)
  - Center block serves as coupling element (C)
  - Remaining blocks are transducers (B,D)

- **Tune response of each segment tuned by varying coupling of finger to piezoelectric film**
  - Use finite-element and coupling-of-modes modeling to predict and synthesize filter bandshape and response

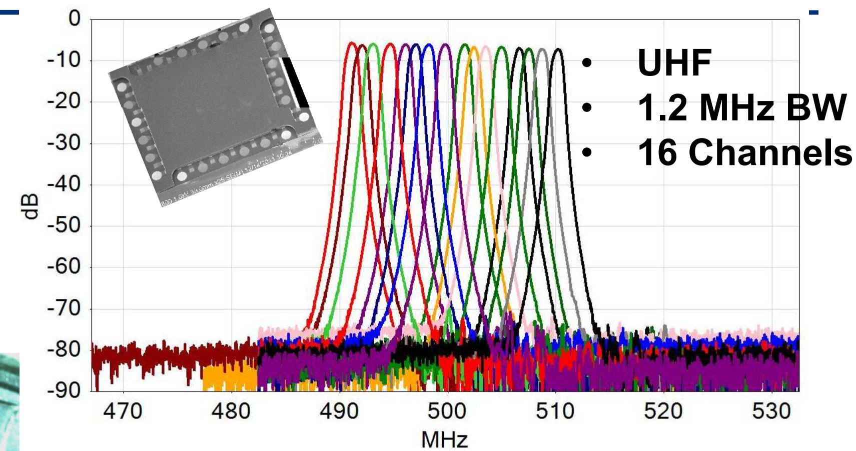
- **Realize fingers using individually addressable MEMS devices**

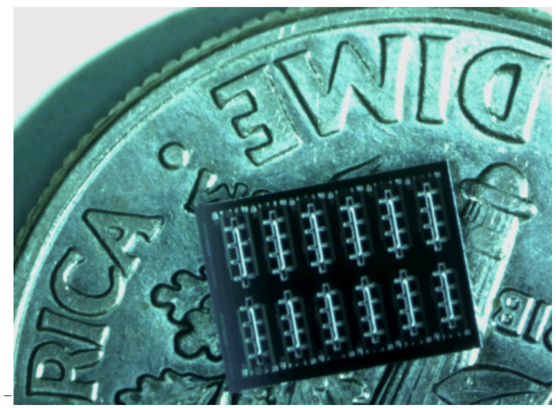
Differentiating Technical Achievements

- **First use of MEMS switches for on/off switching of piezoelectric resonators/filters**
  - No demonstrations of switching MEMS piezoelectric resonators prior to this effort.
  - Current Result: On/Off switching demonstrated, reconfigurability not demonstrated yet but expected by end of Stage I.
- **On/off piezoelectric switching enables band- and shape- reconfigurable high-Q filters**
  - New class of piezoelectric filters with higher Q response than previously demonstrated by reconfigurable electromagnetic filters.
  - Current Result: Filters designed and wafers in fab, with measurements expected by the end of Phase I.
- **First integration of MEMS resonators and capacitive switches**
  - Enables reconfigurable piezoelectric and electromagnetic components on a single die, with potential for post-CMOS integration.
  - Current Result: Demonstrated integration of capacitive MEMS switches with AlN resonators in single integrated process flow. Continuously improving process for performance, yield, and reproducibility.

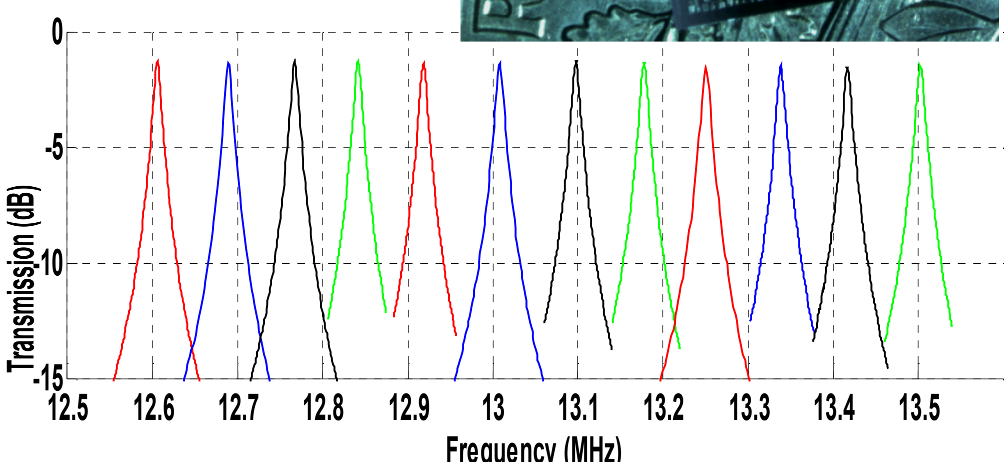
Context: Sandia AlN Filter Efforts

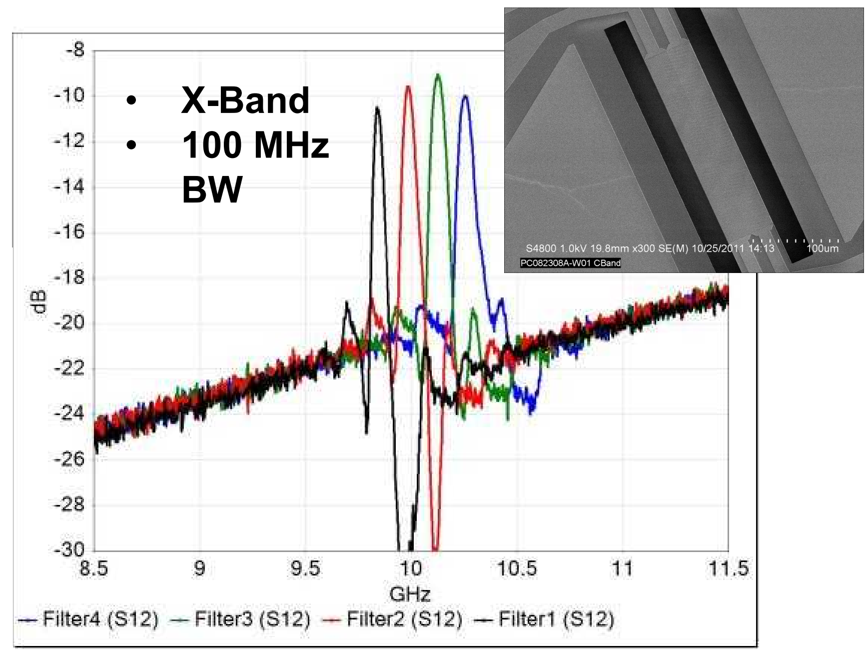
- Filter Banks for Cognitive and Multi-Band Radios
- Filter Arrays for Fast Spectrum Analysis
- Anti-Jam and Secure Adaptive RF Front-Ends
- Ultra Small Footprint (Wafer Level Packaging)
- Temperature Compensation
- High Rejection
- HF to X Band





- **HF-Band**
- **25 kHz BW**
- **12-Channels**





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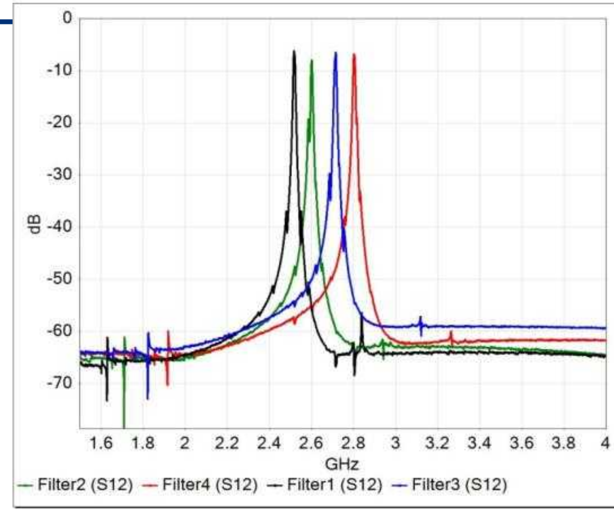
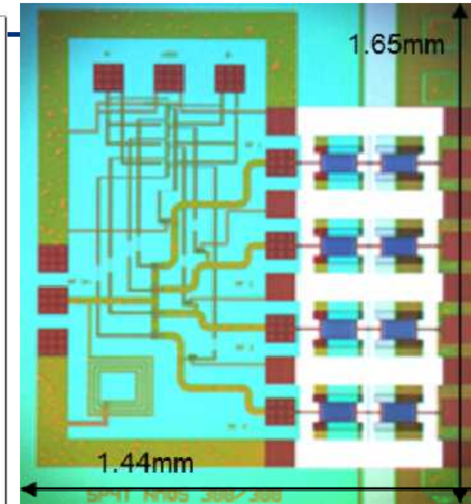
Switched Filter Arrays vs. RF FPGA

Traditional Approach

- Acoustic Filter for Each Frequency
- Selection Using CMOS Electronic Switches
- Large Area
- # of Filters (Bands) Limited by Switch $R_{on}C_{off}$

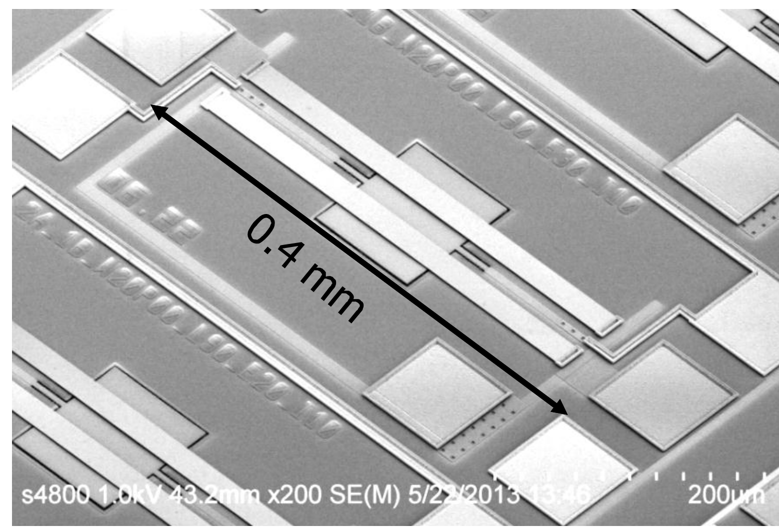




S-Band 4-Channel Switched Filter Array

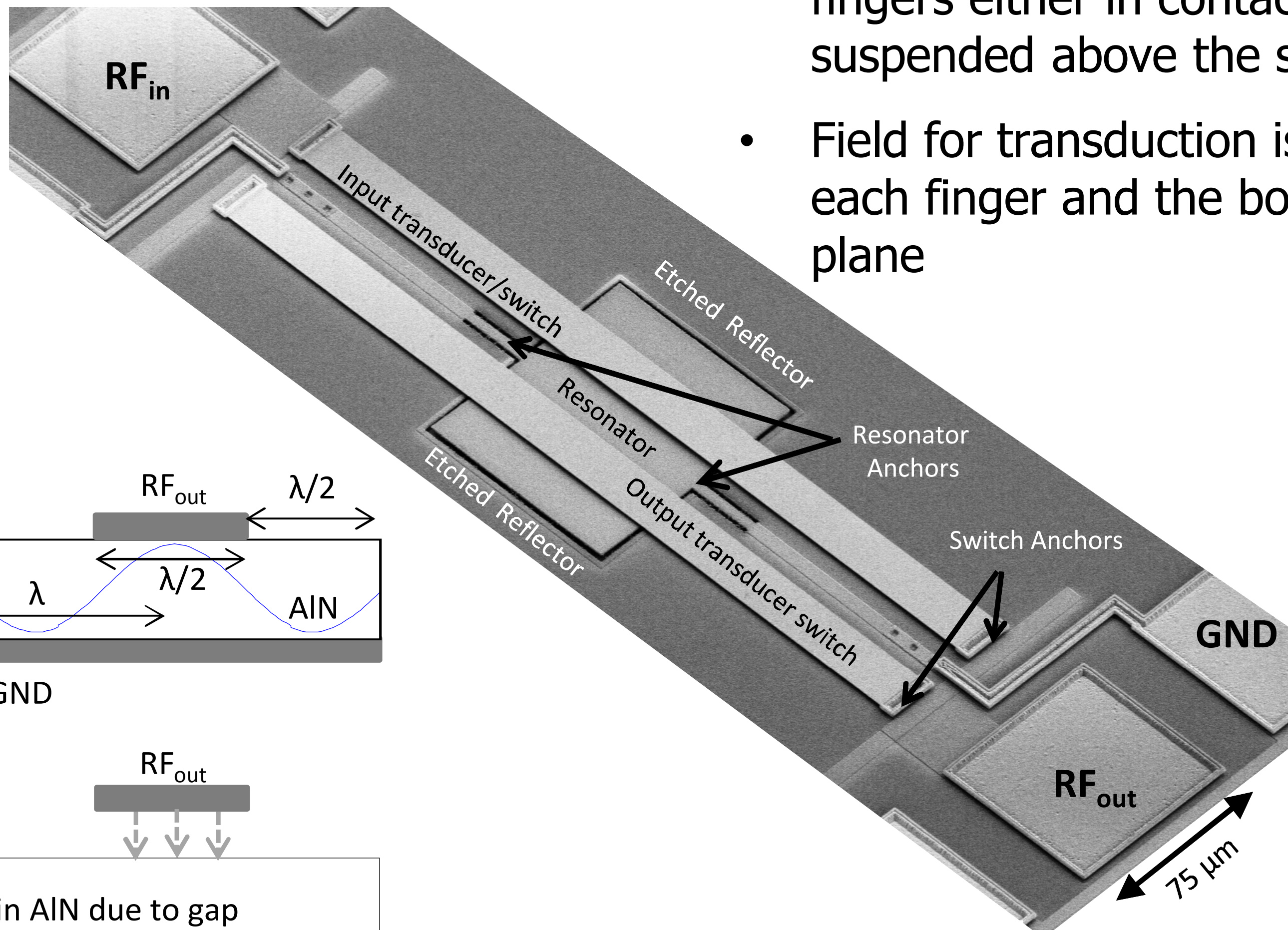
RF FPGA Programmable Filter Approach

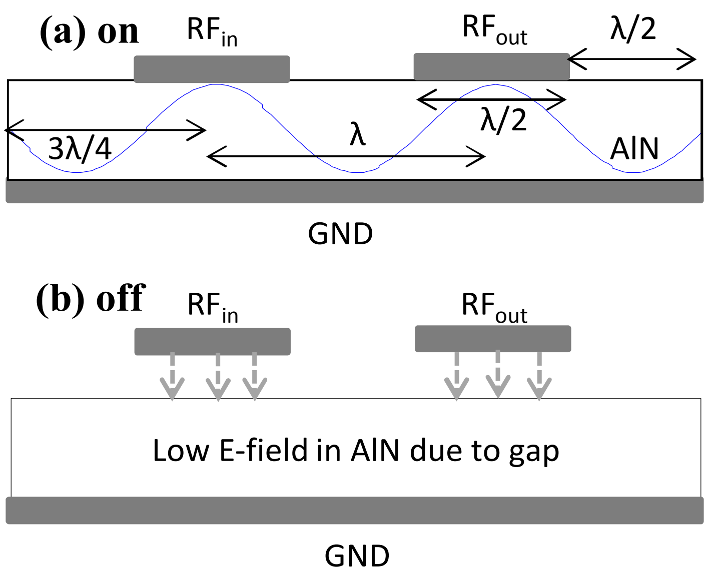
- Single Acoustic Structure Covers Multiple Bands and Channels
- Frequency Programmed Using Suspended Electrodes
- Much Smaller Size
- Ultimately Supports a Much Larger Number of Filter Frequencies



On/off switched resonator design

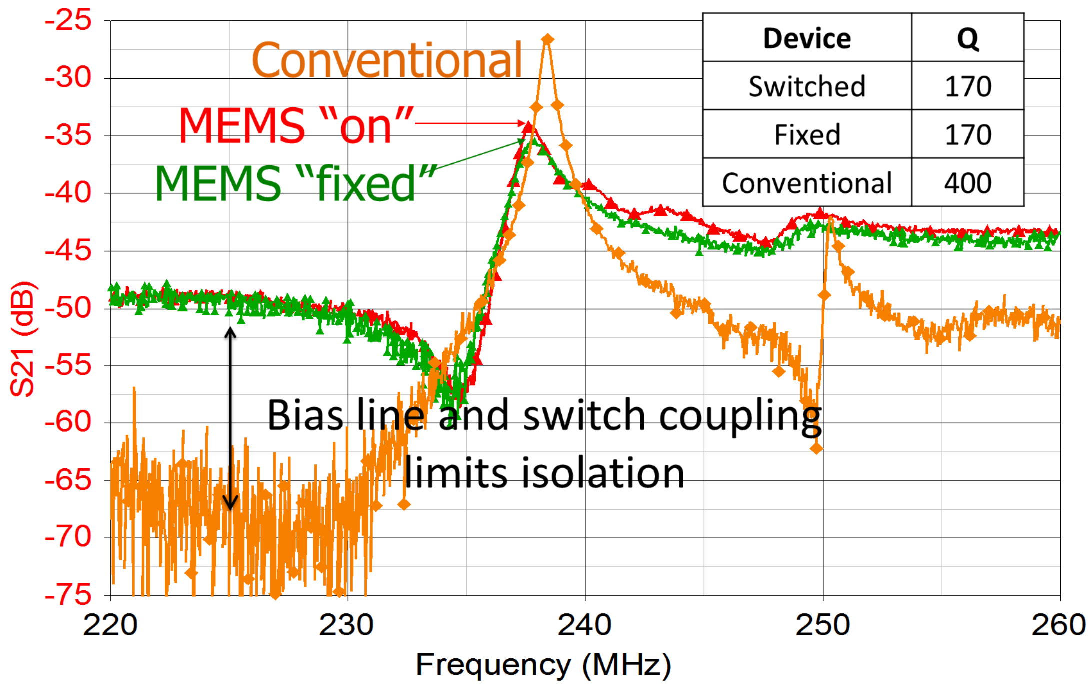
- Two-port single resonator with fingers either in contact or suspended above the substrate
- Field for transduction is between each finger and the bottom ground plane





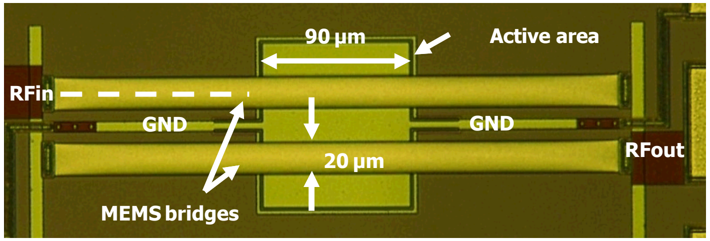
First Results (11/2012): Switched vs. Fixed Resonator

- Both fixed and switched resonator has poorer response than conventional structure
- Isolation of switched structure is inferior to conventional structure
- More discussion later

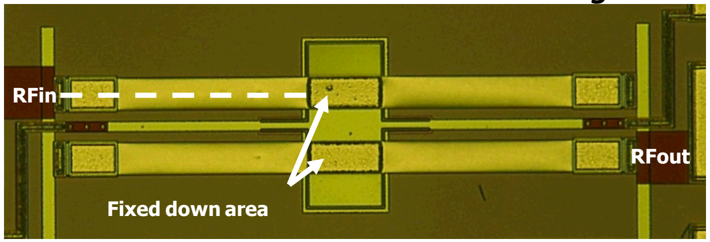


Device	Q
Switched	170
Fixed	170
Conventional	400

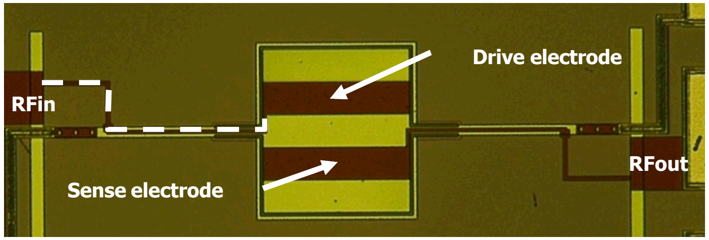
MEMS-Switched Resonator



Resonator with Fixed-Down Active Region

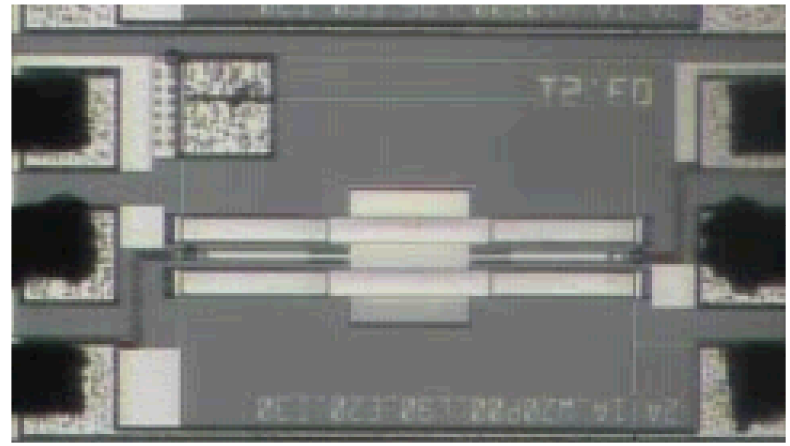


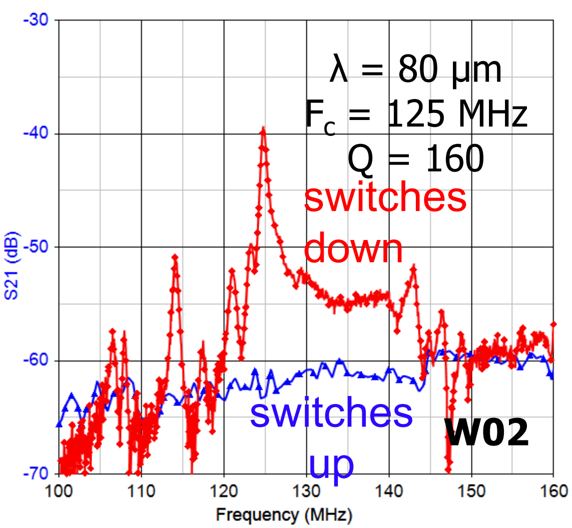
Resonator with Fixed Conventional Feed

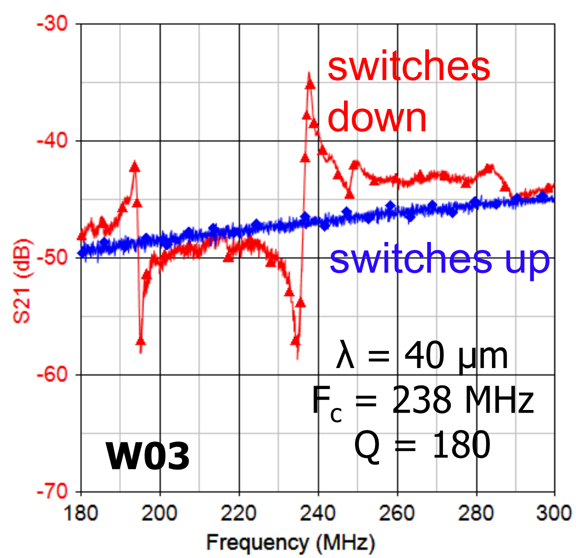


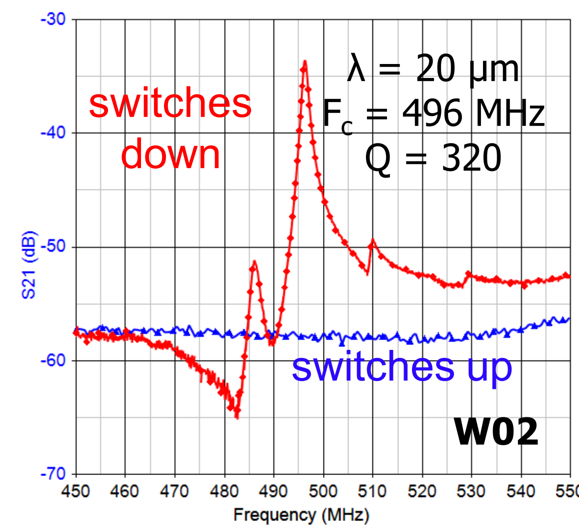
Switched Resonators at Three Wavelengths

- Switched piezoelectric resonance demonstrated at 125 MHz, 238 MHz, and 496 MHz
- Devices are high impedance to allow demonstration with minimum number of switches
- Q ranges from 160 – 320
  - Appears to increase with frequency (increasing aperture width in λ)



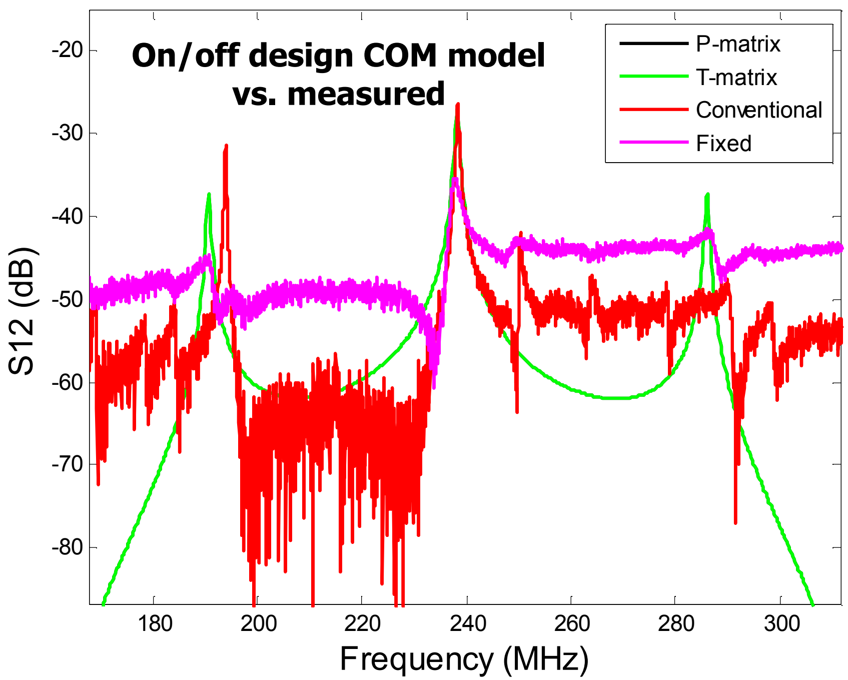


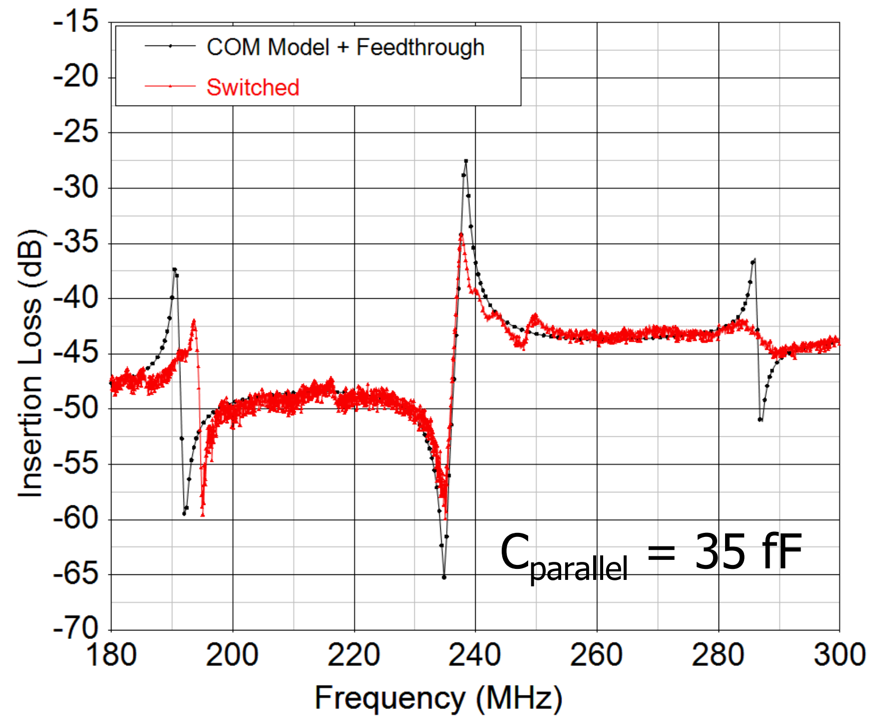




Coupling of Modes Modeling Results

- Coupling of modes modeling accurately predicts on/off design
  - Conventional design predicted by regular COM model
  - Switched case requires addition of feedthrough capacitance for accurate model
  - Does not capture the reduction in Q due to additional damping
  - FEM values were used, except that velocity was adjusted by 1.8%



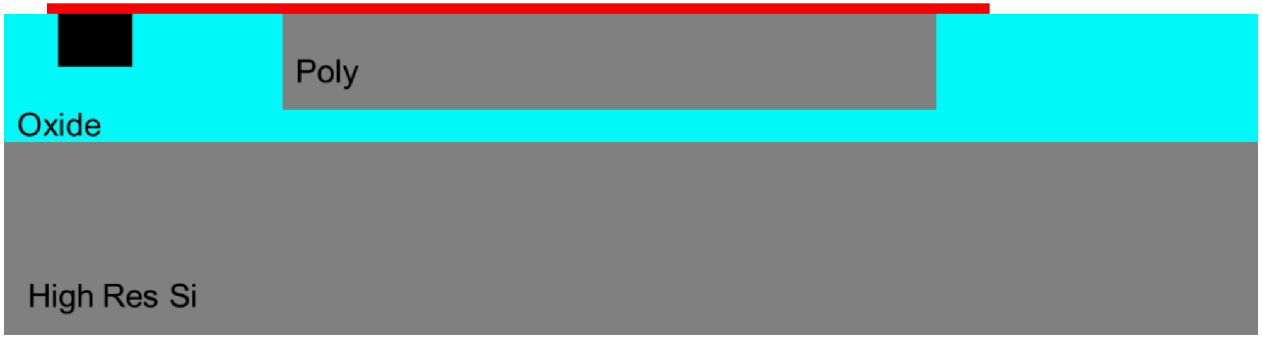


Fabrication Flow (1)

- Deposit poly-silicon on oxidized high-resistivity Si wafer

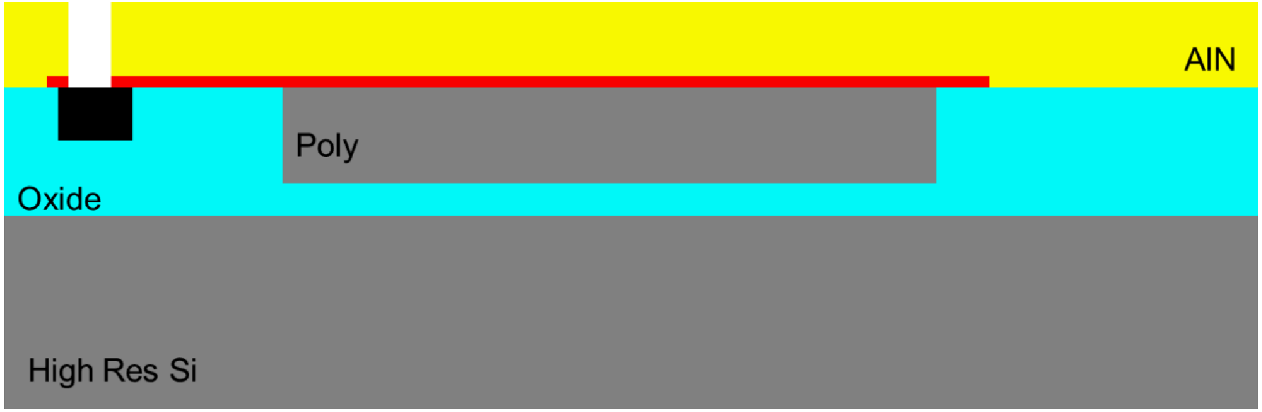
- Deposit additional SiO_2 and polish flat to reveal poly-Si island

- Etch opening in oxide, deposit W etchstop, polish flat, and deposit and etch lower TiAl electrode

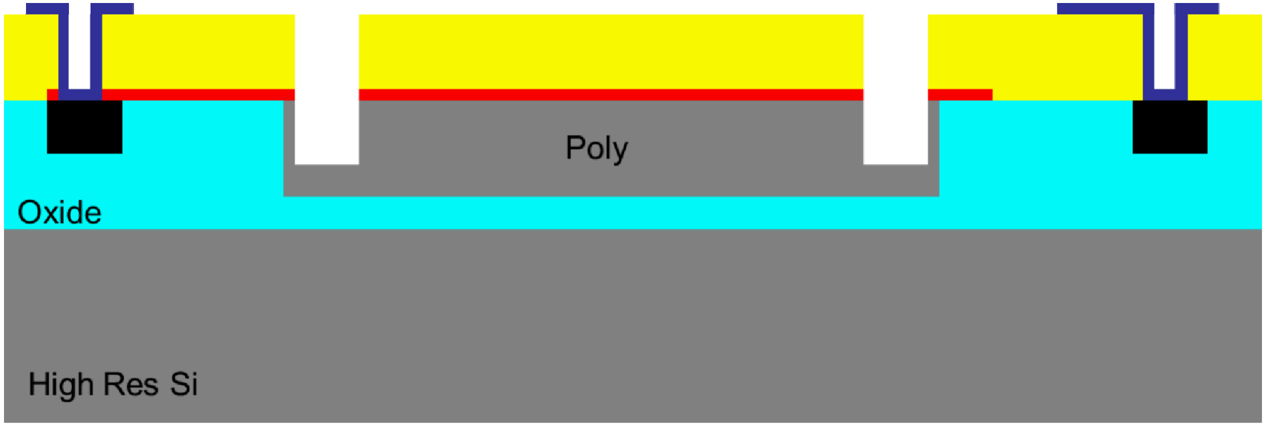


Fabrication Flow (2)

- Sputter deposit AlN piezoelectric layer and etch contact openings to bottom metal



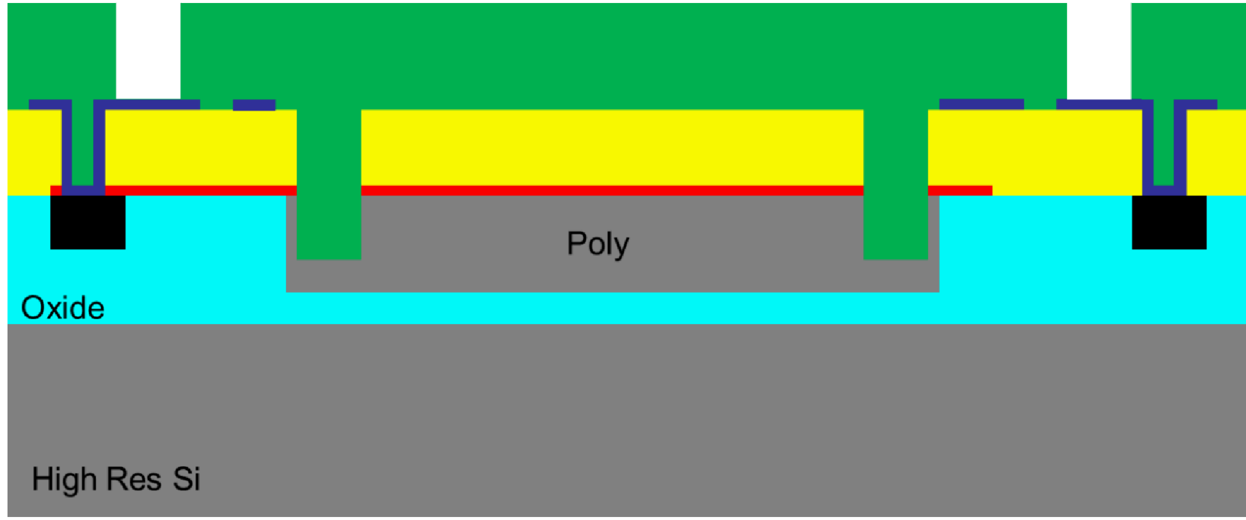
- Deposit and etch resonator TiAl upper electrode; etch release openings through AlN to expose poly-Si sacrificial layer



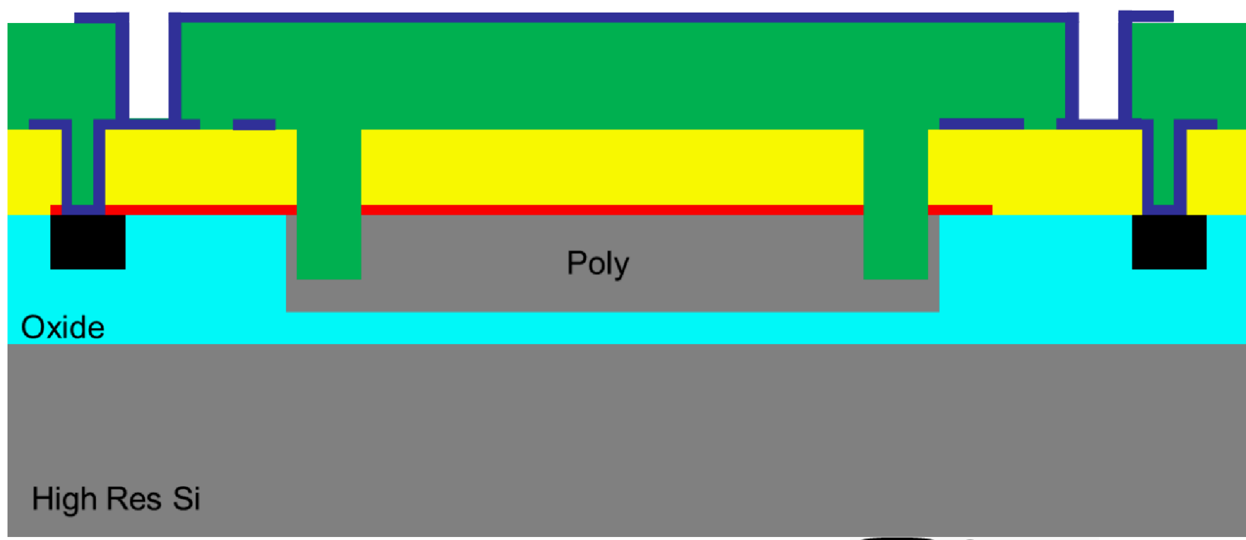
- Other than the MEMS release step, this completes the AlN microresonator structure

Fabrication Flow (3)

- Deposit, polish, and etch SiN switch sacrificial layer

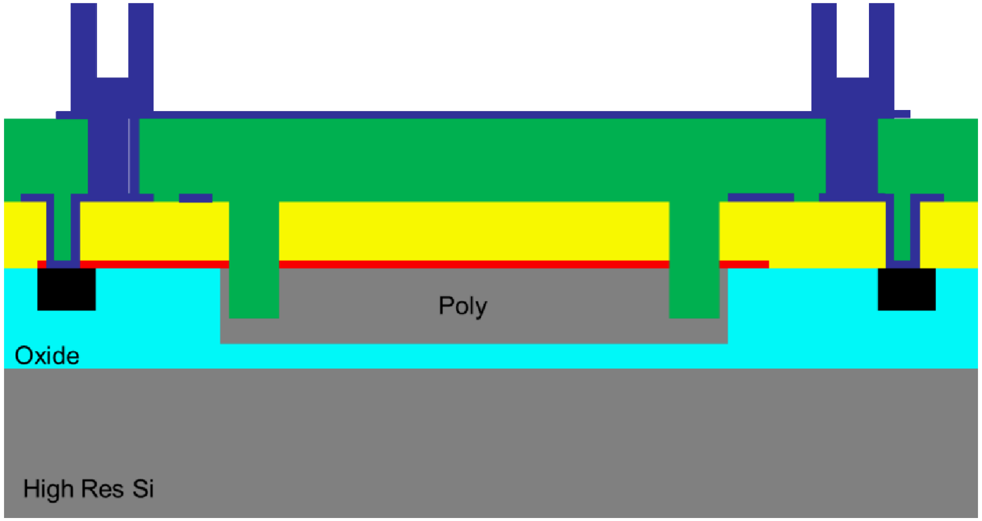


- Deposit and etch Ti/Al switch bridge metal

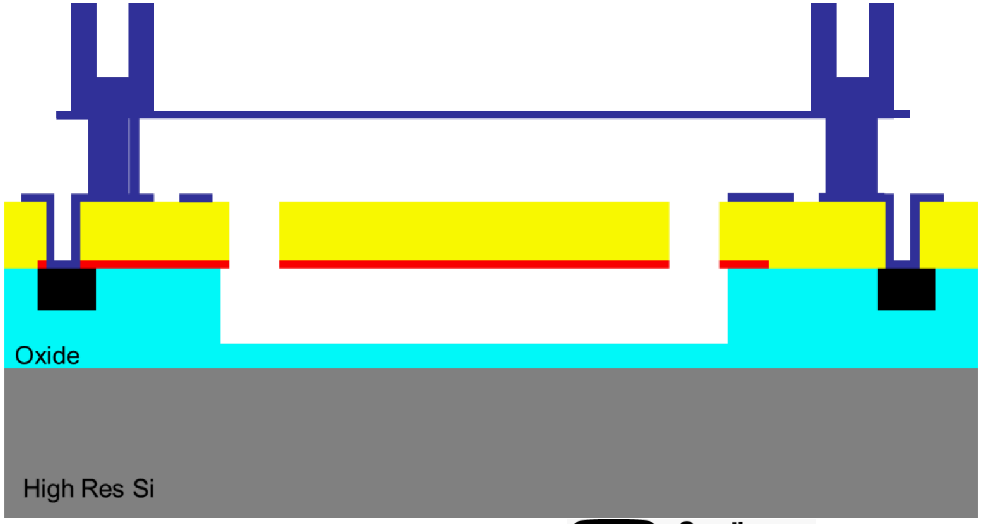


Fabrication Flow (4)

- Deposit and etch thick anchor and beam reinforcement TiAl

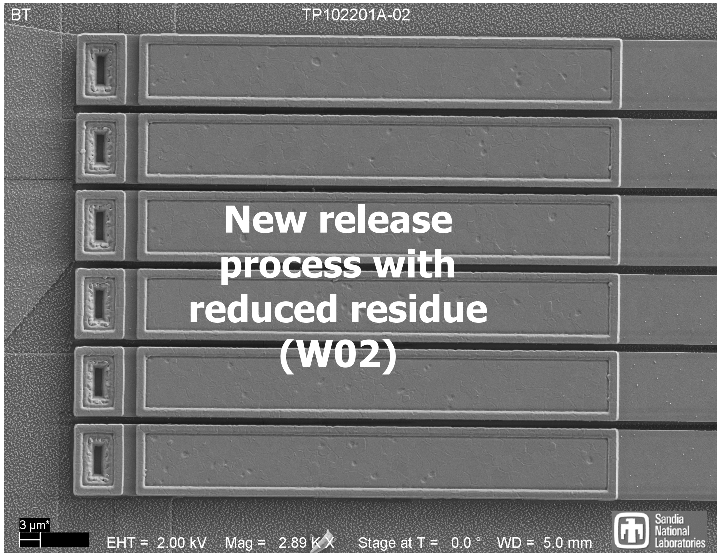


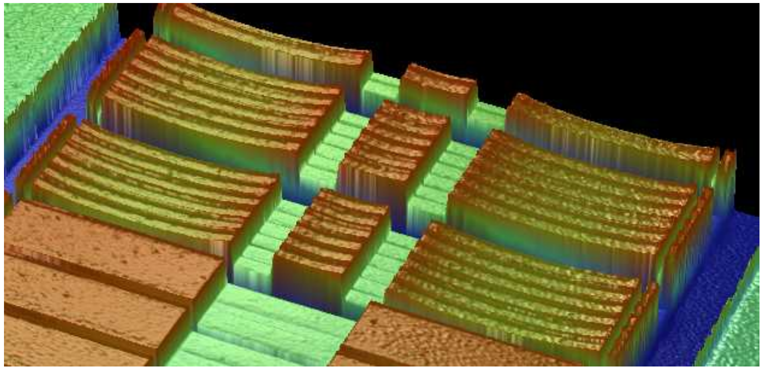
- Etch poly-silicon and Si_3N_4 sacrificial layers to release MEMS devices



Fabrication Challenges

- **Opening of deep vias in Si_3N_4 stopping on Al**
  - Very difficult etch when nitride thickness > 1.5 μm
  - Thicker layers will require alternate etchstop layer over Al (under development)
- **Post-release residue on switches**
  - Lowered device Q and caused switch stiction
  - Traced back to top of SiN sacrificial layer
  - Solved by blanket etch of SiN prior to bridge metal
- **Metal stress in bridges**
  - High residual stress increases pull-in voltage
  - Metal stress causes curvature along reinforced sections





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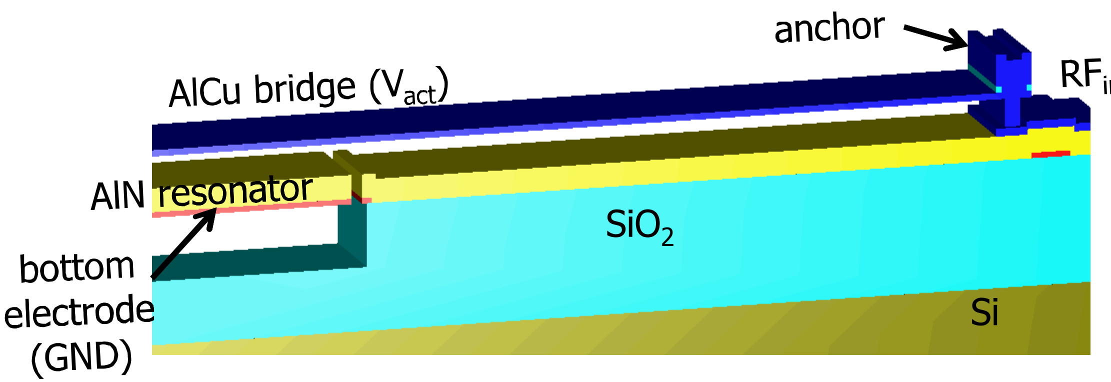
MEMS Switch Designs and Concept

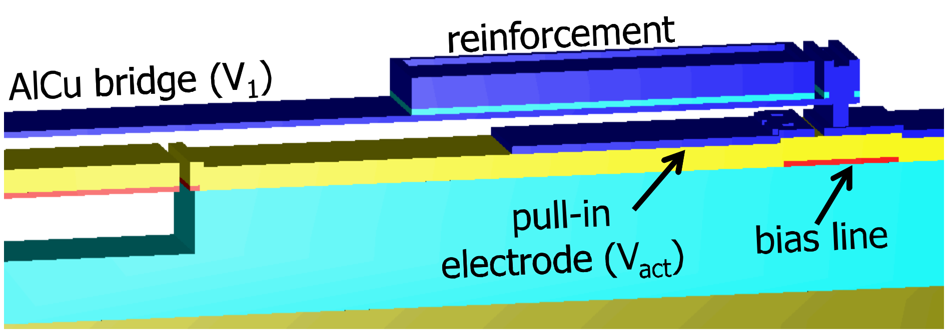
1. Standard capacitive switch

- Pull-down voltage between bridge and bottom electrode
- Simple design, ensures good contact, susceptible to charging, cannot be independently addressed



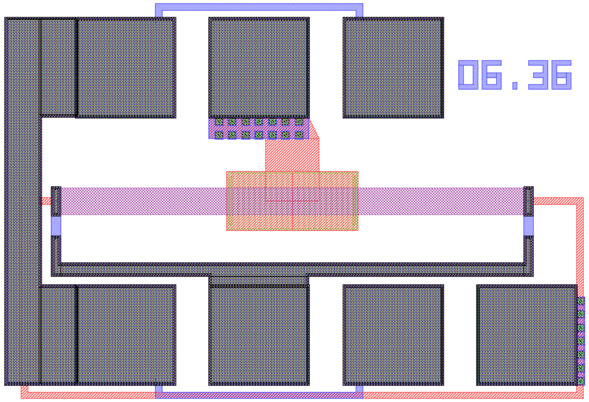
2. Pull-in electrode near anchor

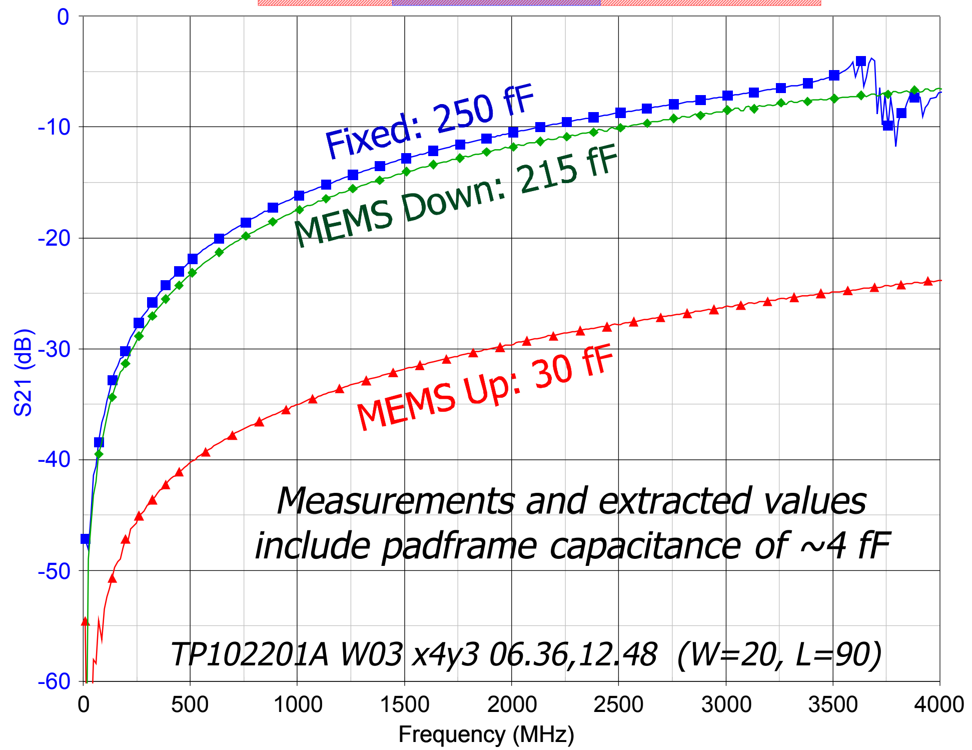
- Less susceptible to charging, separate RF & bias allows individual addressing
- Requires some bridge biasing to ensure intimate contact
- Actuation electrode moved underneath AlN dielectric to prevent electrode shorting in revision of first mask



Capacitive Switch Measurements

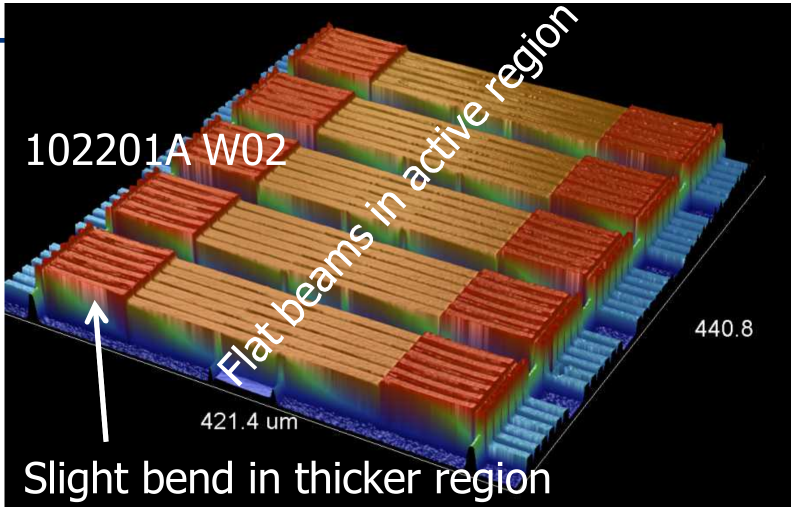
- **Measured data from "standard" capacitive switch**
  - Fixed down capacitance density is 0.14 +/- 0.01 fF/μm²
  - Down-state capacitance is 70-85% of fixed down switch – suggests average gap ranging from 10-30 nm.
    - AlN rms roughness ~2 nm
  - Upstate capacitance is 3x higher than predicted from parallel-plate approximation at intended bridge height
    - Thicker sacrificial layer thickness will reduce up-state capacitance to AlN

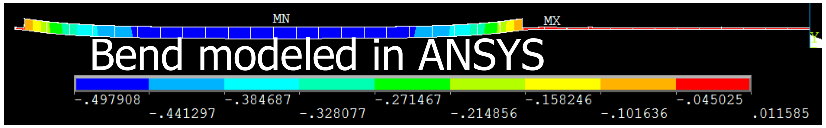


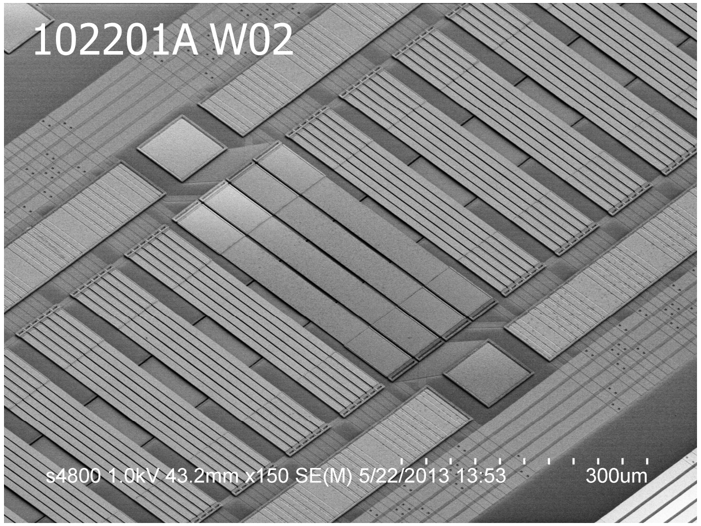


Switch Modeling and Characterization

- **Stress characterization**
  - Beams are tensile stressed, behaving more like "strings" than beams
  - Some curvature in thicker sections due to tensile stress and non-uniform cross-section (r_c=9mm)
  - The stress state observed in the first lot is adequate for this work, but causes limitations with making intimate contact
  - Switches used for Bragg reflectors have reinforced center section – additional challenges with curvature

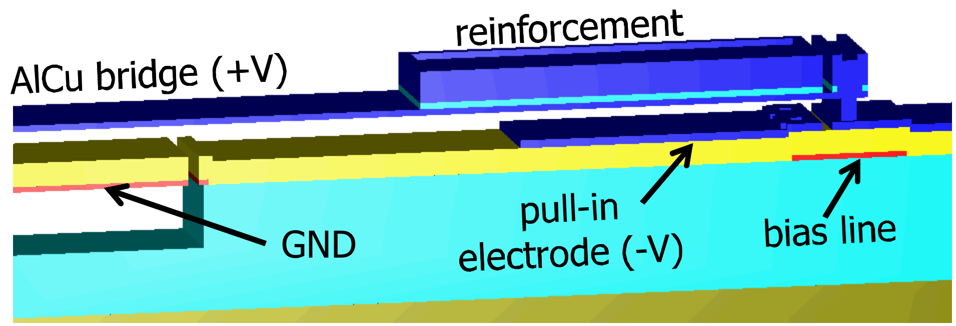


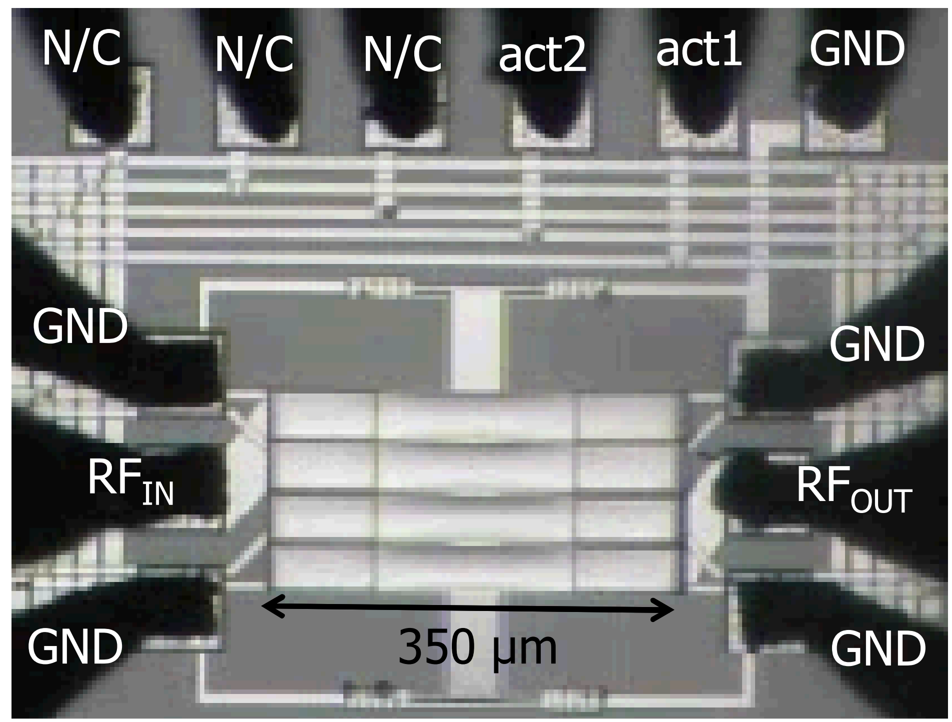




Actuation of Individual Switches

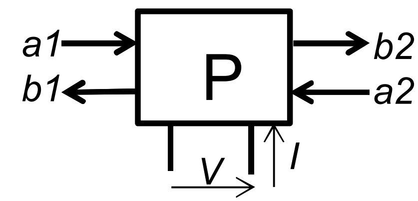
- **Addressable Switch Actuation**
  - Required for complex programmability of transducers and Bragg reflectors
  - Biasing conditions relative to bottom ground electrode
    - Bridge: +
    - Edge pull-in electrode: -
  - Both bridge and edge electrode must be biased to close switch
  - Example transducer shown
    - Bridge connections: 1+2, 3+4
    - Edge electrodes connections: 1+3, 2+4
    - Bridges at 0V or +8V
    - Edge electrodes at +8V or -16 V
    - Switches actuate when both the bridge and the edge electrodes are biased





Acoustic Interface Physics and Model Building Block

Mixed Scattering Matrix

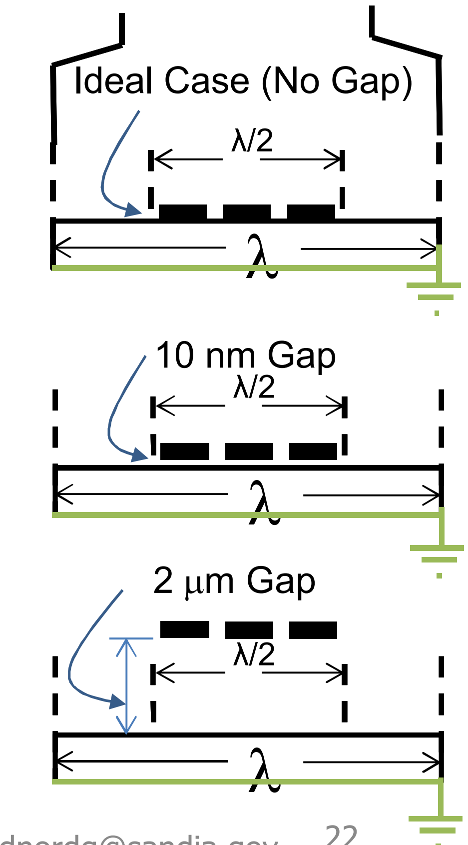


$$\begin{bmatrix} b_1 \\ b_2 \\ I \end{bmatrix} = \begin{bmatrix} P_{11}(\omega) & P_{12}(\omega) & P_{13}(\omega) \\ P_{21}(\omega) & P_{22}(\omega) & P_{23}(\omega) \\ P_{31}(\omega) & P_{32}(\omega) & P_{33}(\omega) \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ V \end{bmatrix}$$

<u>Model:</u>

- The mixed scattering matrix (P) is computed from the COM parameters and represents the simplest periodic device building block.
- *What happens to the COM parameters for **active** (10nm) and **inactive** (2μm) fingers:*

Case	Velocity	Reflection	Acoustic Coupling	Static Capacitance
No Gap	1	1	1	1
10 nm Gap (active)	1.05	0.81	0.98	0.88
2 μm Gap (inactive)	1.06	0.11	0.0011	0.11

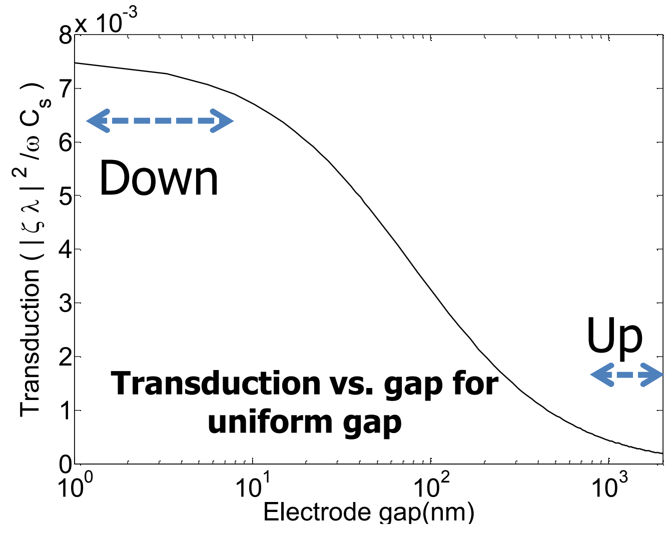


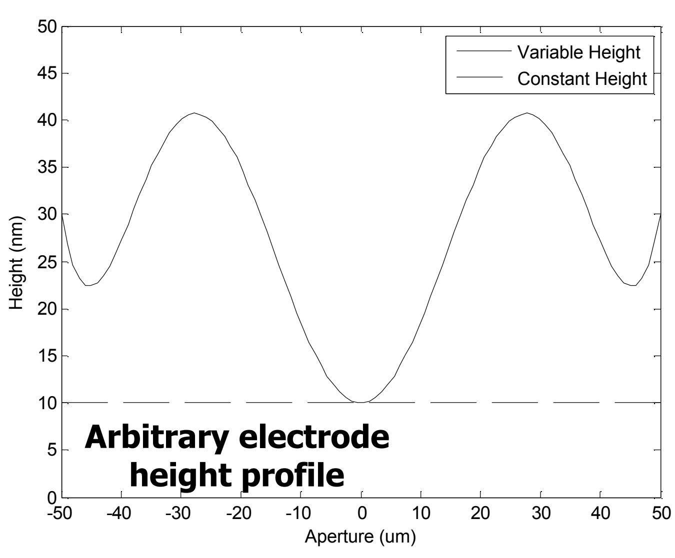
<u>Takeaways:</u>

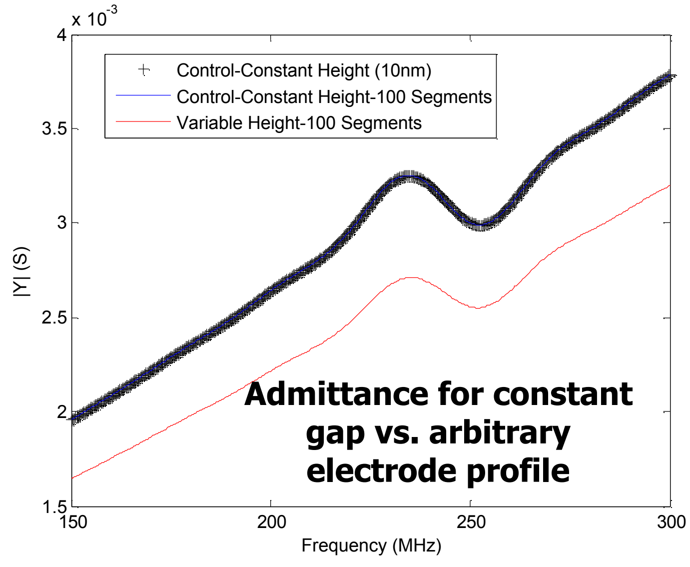
- Imperfect contact to the AlN causes negligible decrease in transduction.
- Uniform imperfect contact causes significant reduction in reflectivity.
- Breaking the fingers into three does not impact transduction

Imperfect and Non-Uniform Finger Contact

- Modeling to determine the impact of imperfect and non-uniform contact on the performance of a transducer electrode
- Imperfect contact: transduction is within 90% of fixed down value for nm-scale gaps
- Non-uniform contact: admittance and transduction is similar to uniform gap of same average distance
- For Bragg reflectors, loss of contact significantly drops reflectivity (reflection is primarily mechanical)

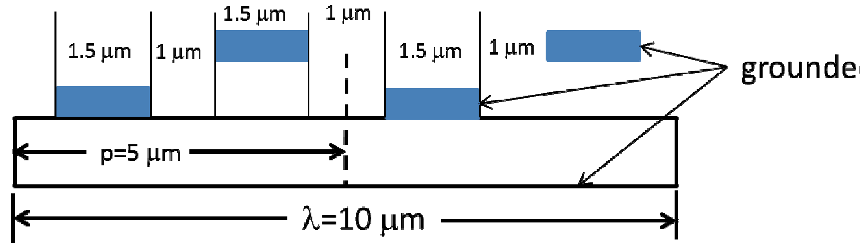




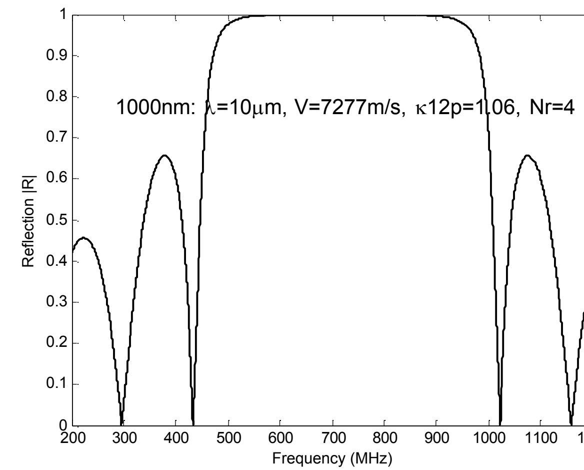


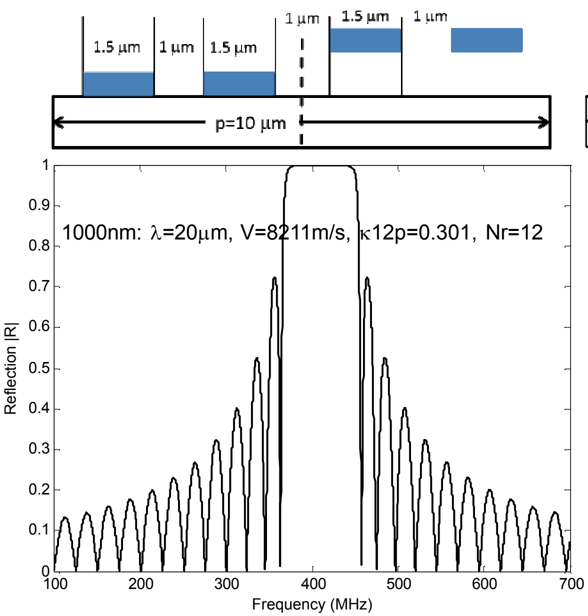
COM Modeling of Tunable Bragg Reflectors

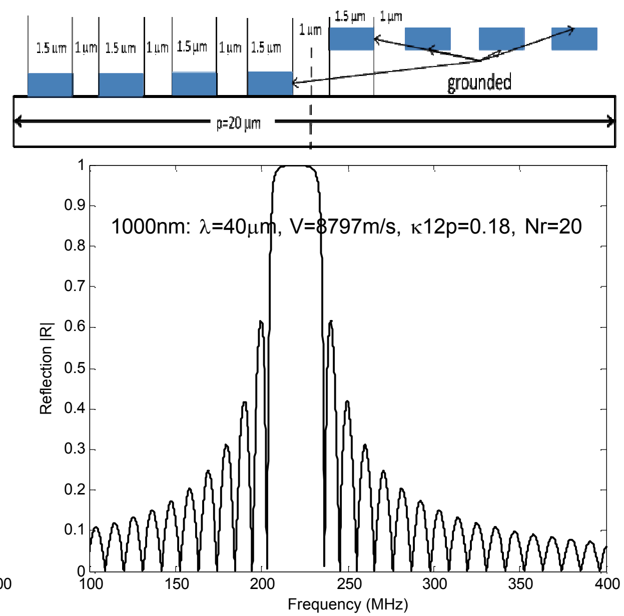
- **Bragg Reflector Unit Cell**
  - 1.5 µm fingers on 2.5 µm pitch
  - Shortest wavelength: 10 µm (F ~ 800 MHz)



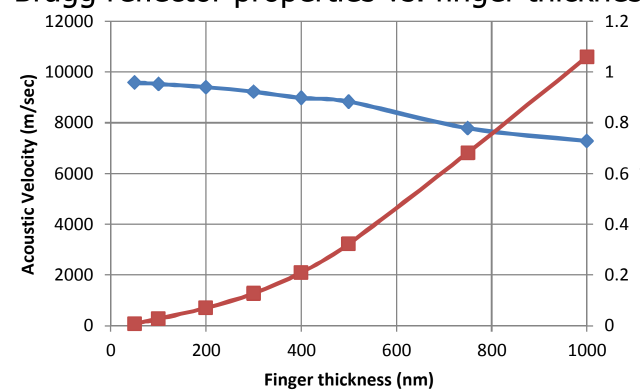
- **Modeling Results**
  - Loading from thicker finger slows down wave by ~20%
  - Bragg reflectivity depends upon mechanical contact







Bragg reflector properties vs. finger thickness



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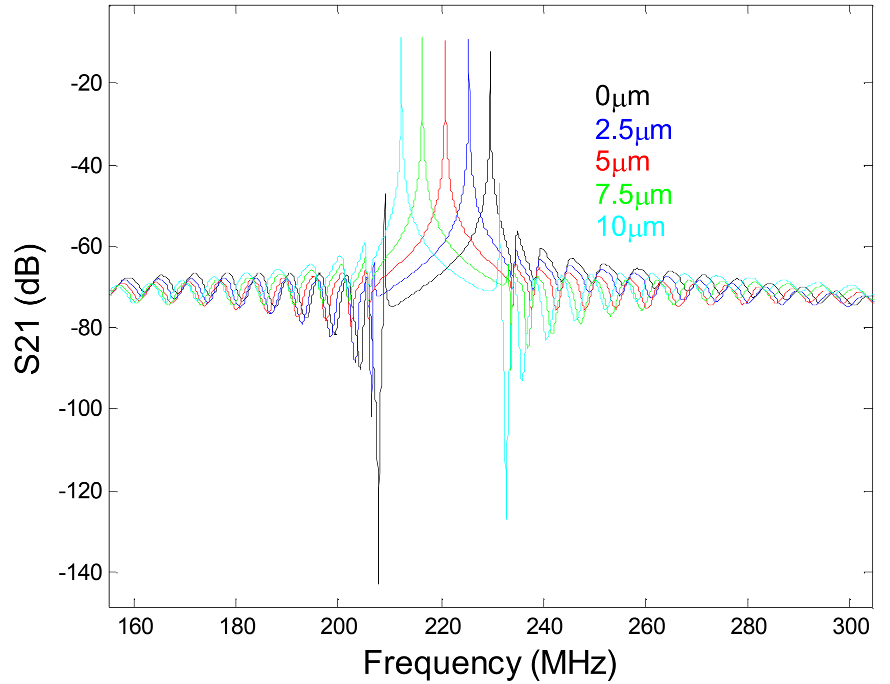
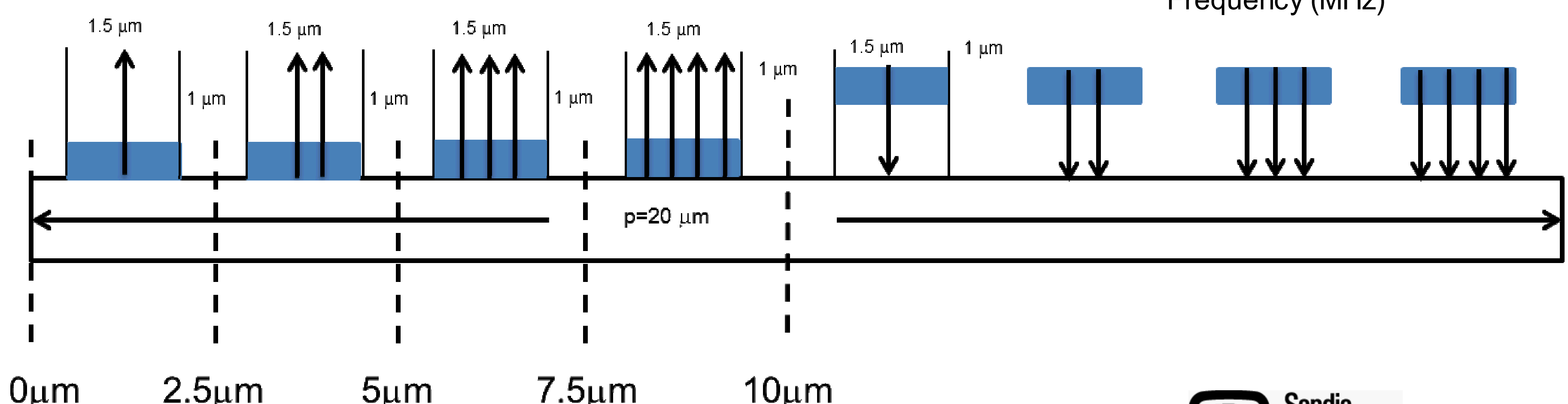
Tuning by Varying Gap from Transducer to Reflector

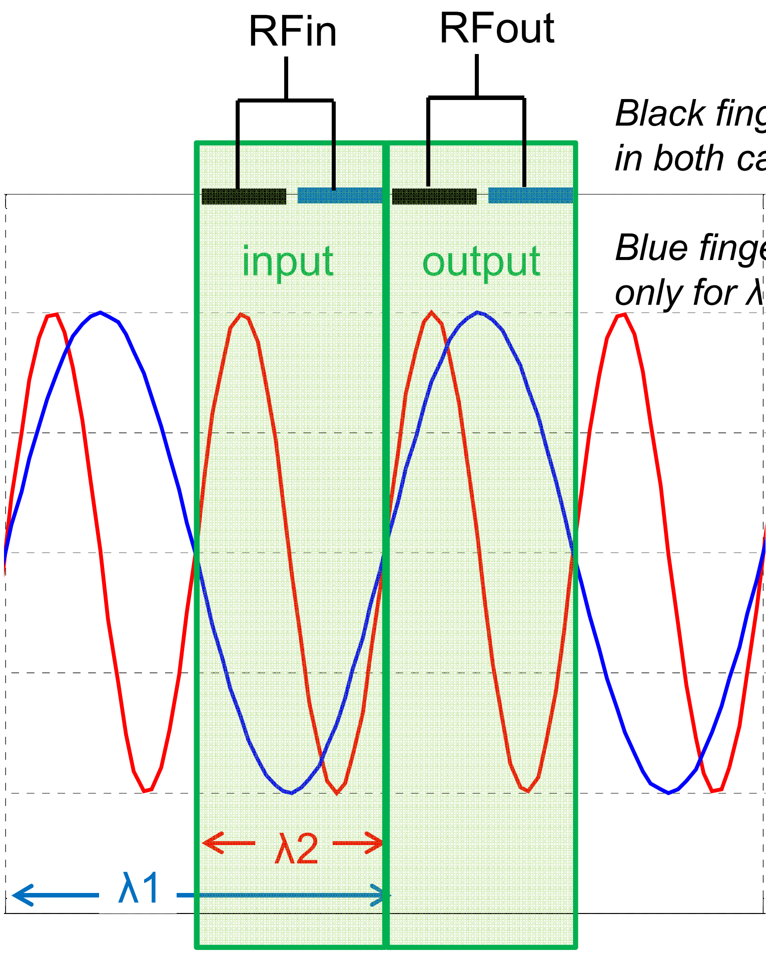
- **Can tune cavity length by tuning point along array where reflector begins**
  - Example: 40 μm wavelength with 2.5 μm fine-tuning
  - Transducers and Bragg reflector are sufficiently broadband to allow for varied center frequency
  - May also be able to take advantage of difference in velocity with mechanical loading





F/2F Design w/ Etched Reflector

- Switch between a frequency and second harmonic
- Designs fabricated and tested but demonstrate poor response
    - Inadequate aperture width + larger (40 μm) fingers

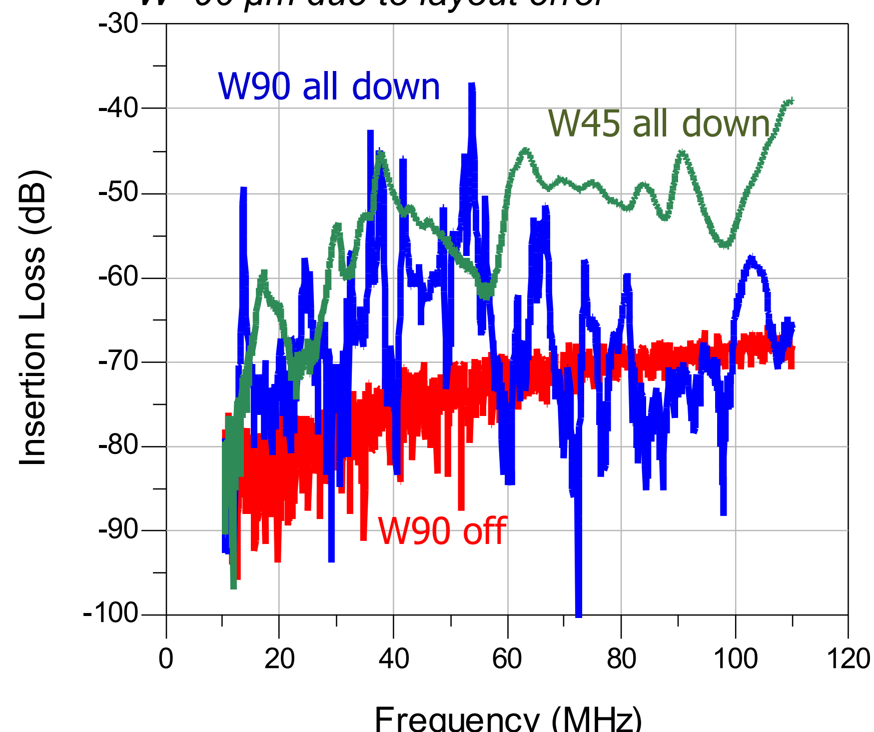


Black fingers – down in both cases

Blue fingers – down only for λ1, up for λ2

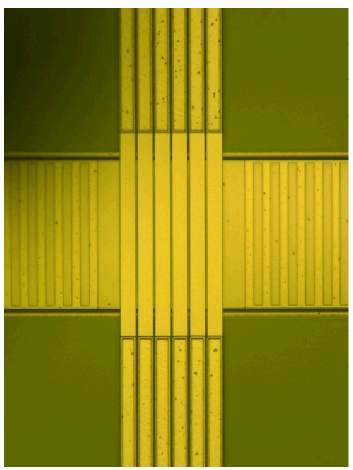
Marked difference in Q between W=90 μm and W=45 μm – difference in aperture width

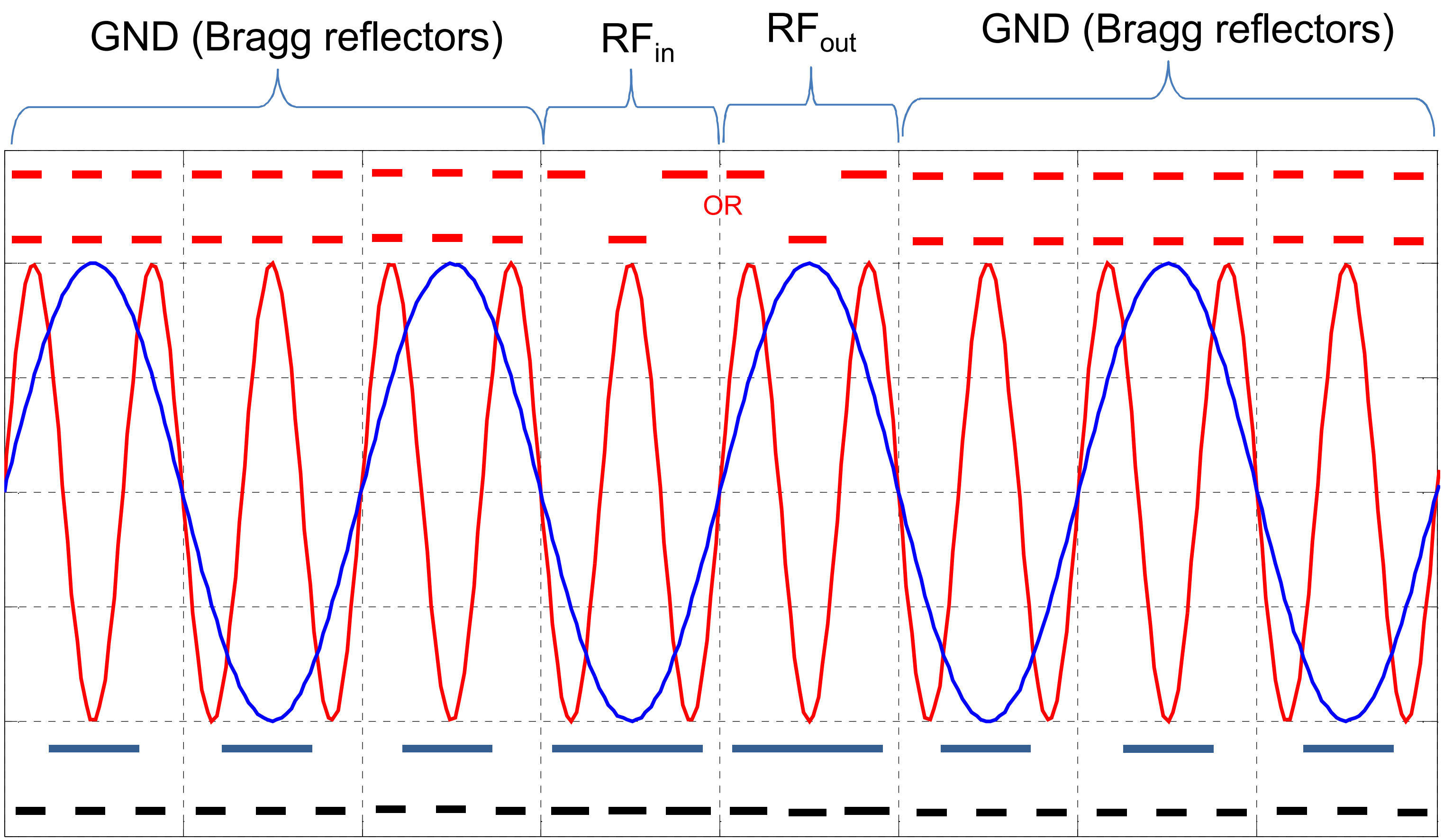
Unable to actuate fingers separately on W=90 μm due to layout error



F/3F Design w/ Bragg

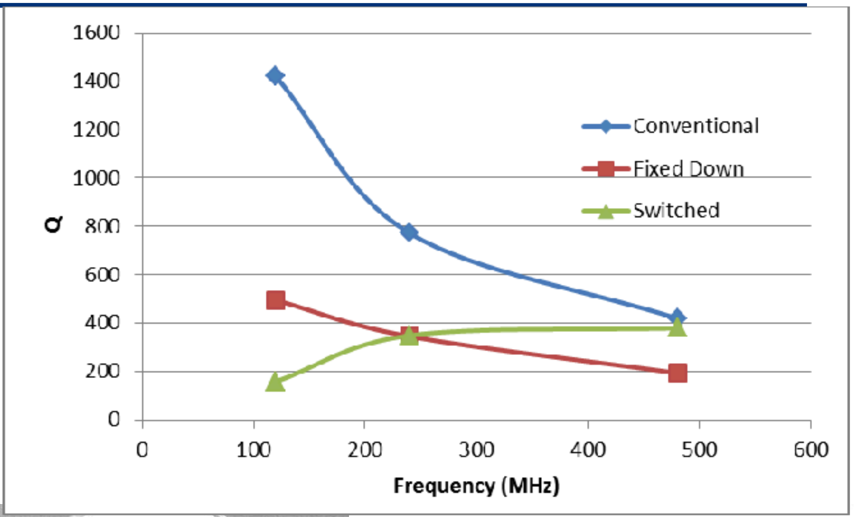
- Design with switched transducer fingers and fixed Bragg fingers
- Colored lines show fingers that are in contact with substrate for given operation
- Bragg is not reflective enough – probably not in contact with AlN due to stress

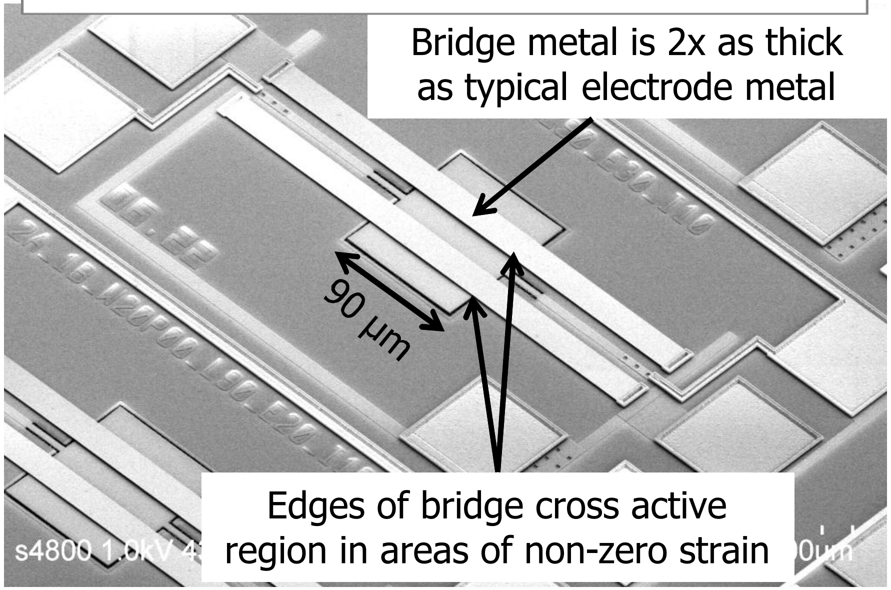




What is Limiting Q?

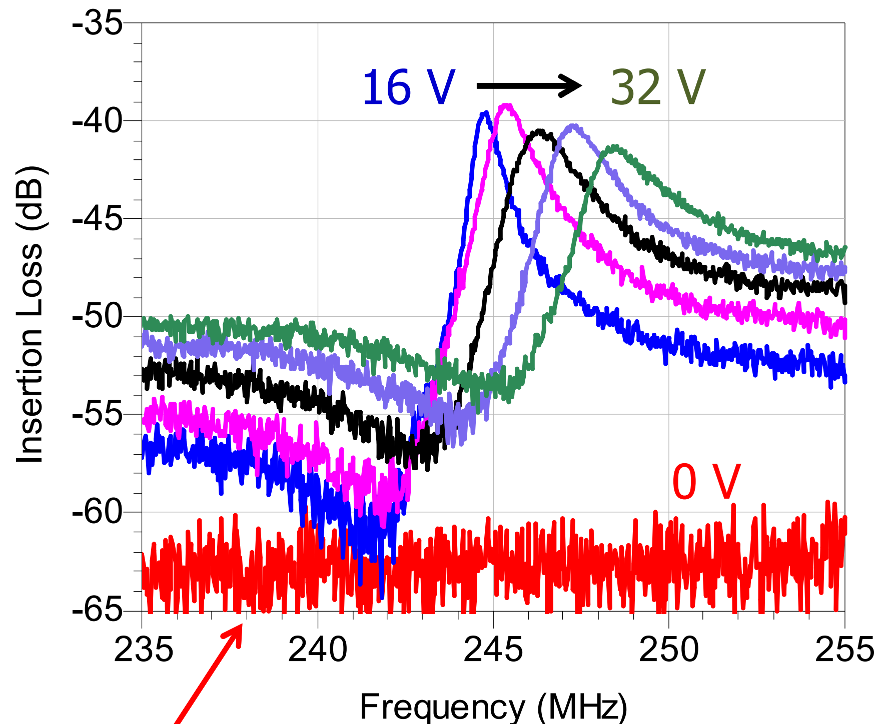
- Q values
  - Q of switched structure is ~300 at 240 MHz
  - Q of conventional structure is ~800 at 240 MHz
  - Typical Q of ideal AlN device is ~1800
- Other trend to consider
  - Q of switched structure **increases** with frequency
  - Q of conventional structure **decreases** with frequency
  - Suggests that anchor losses, rather than interface losses, are dominating
- Why is the switched device Q lower than the conventional device Q?
  - Damping due to thicker bridge electrode
  - Damping due to bridge edges crossing active region at points of non-zero strain (strain null is at the center of the bridge)
  - Only using two electrodes limits transduction





Voltage Tuning

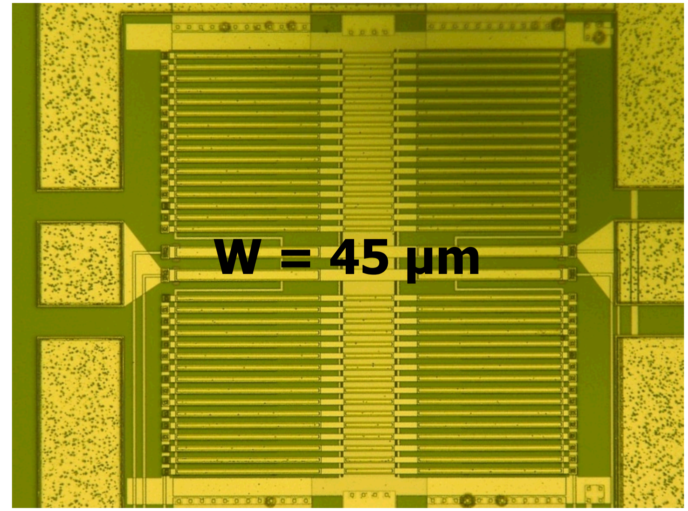
- **Observed ~0.2 MHz/V tuning after pull-in on two-switch designs**
  - If understood, offers additional tuning mechanism
  - Provides hints about factors limiting Q
- **Trends**
  - Q **decreases** with increasing voltage
  - Resonance **increases** with increasing voltage
- **Implications**
  - Both effects appear to be related to applied force
  - Increased voltage -> increased contact -> increased damping
  - AlN membrane may be bending / flexing and changing strain in piezoelectric material

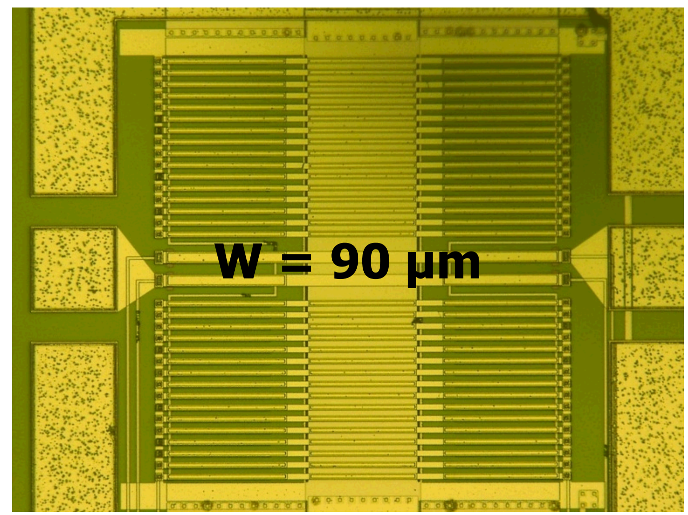


Improved isolation from electrode redesign

Strategies for Improving Q and Insertion Loss

- **Increase aperture width**
  - Loss is caused by damping along edge of resonator
  - Wider aperture will have smaller impact from bridges crossing edges of structure
- **Increase transduction area**
  - Multiple fingers to lower device impedance
- **Novel switch designs**
  - Switches anchored to AlN membrane rather than crossing gap
  - Switches optimized to reduce anchor losses
- **All of these approaches are being explored on a wafer lot that is currently in fab**





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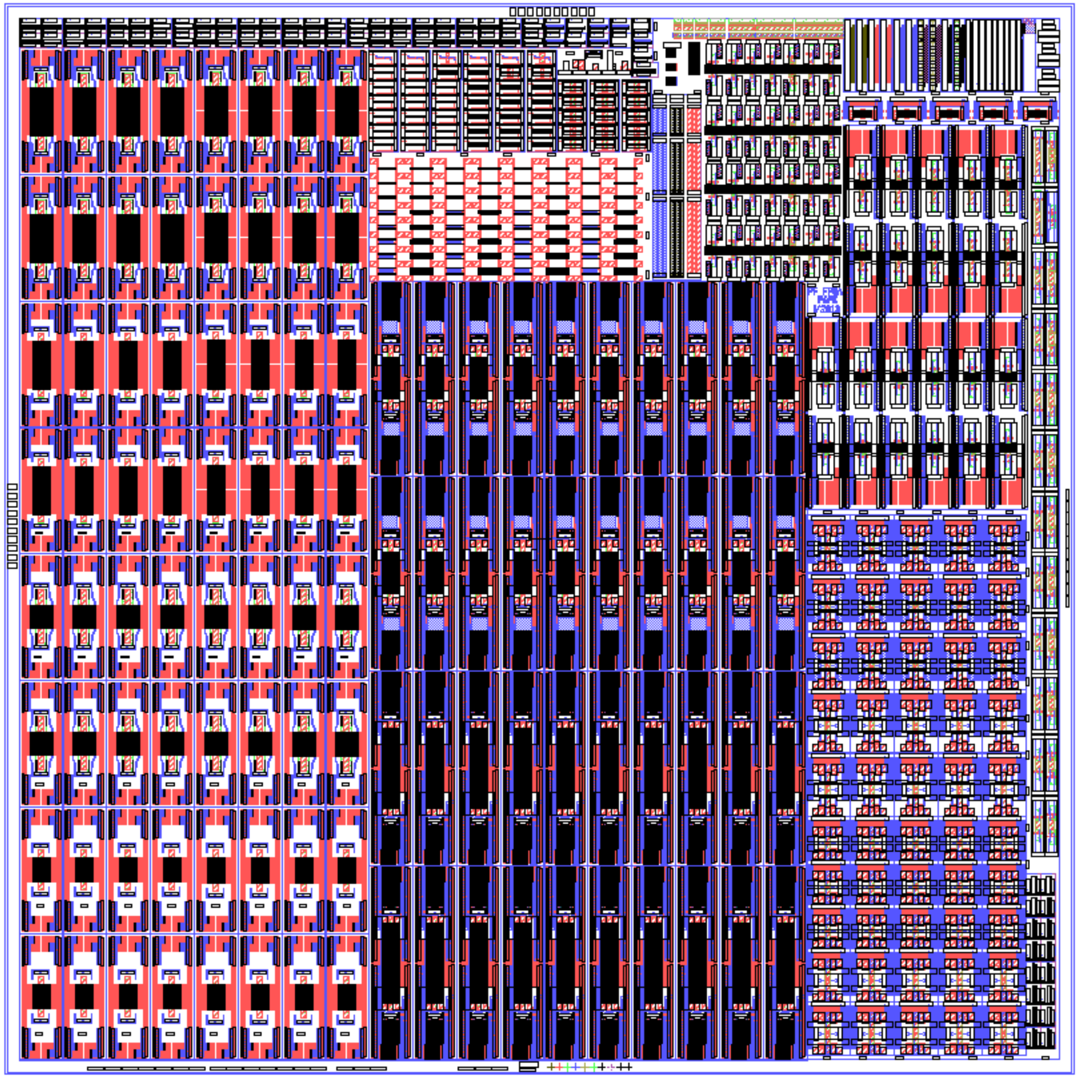
Maskset Currently in Process

- **Applied lessons learned from first fab/test cycle**
  - All devices use a wider aperture
  - More multi-finger devices
  - Reflectors tuned for lower velocity in Bragg gratings
- **Highly reconfigurable filters**
  - 40 finger transducers
  - 64 finger reflectors
- **Transducer and reflector test structures**
  - Bragg coupling structures
  - Bragg fine-tuning structures
- **Fab Due end of August**



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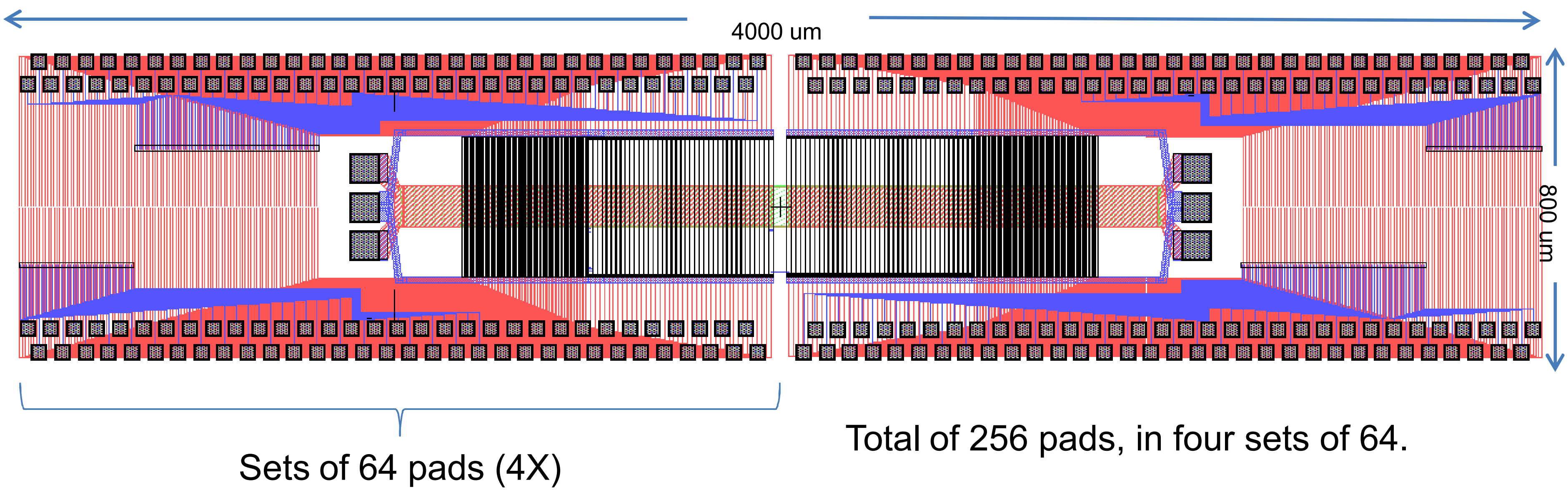
High-Order Transducers and Reflectors

- **Addressing and testing filters with 40-electrode transducers and 64-element reflectors will be a challenge**
- **Test Plan: 256-pin circuit-board based probe card with Labview-addressed switch matrix to drive individual pins**
- **Switch yield and reliability will also be a challenge**



Major Results

- **Piezoelectric transducers can be turned on and off using MEMS**
  - The foundation of the activity, demonstrated from 120 MHz – 500 MHz
  - Scalable to at least 2 GHz (W = 2.5 μm)
  - Transduction is relatively robust with small gap between AlN and switch beam
- **Contact and metal thickness play an important role for Bragg reflectors**
  - Mechanical effects are primarily responsible for reflection – need intimate contact.
  - Thick metal increases reflection, lowers velocity – different pitch for transducer and reflector
  - Bragg-based designs on current mask did not work because they were not thick enough
- **Anchor damping and mass loading are limiting Q in current designs**
  - Q depends on aperture width to decrease influence of anchors.
  - Larger electrodes with more fingers will reduce loss of devices
- **Switches with 3 actuation terminals allow individual addressing**
  - Building block for more complex filters and structures.
  - Some ground-to-bridge bias required to pull electrodes flat on AlN

Comparison to BAA Objectives

- **Can We Aggregate Designs From Five Different Applications?**
  - We believe that this approach can be used to aggregate at least five designs.
  - Need additional effort in designs for higher Q and lower loss (in process)
- **Where Have we Achieved the Goals?**
  - Have achieved Stage I goal of demonstrating functional piezoelectric switching of resonators using MEMS switches.
- **Where Have we Fallen Short?**
  - We have not achieved Q values consistent with those of fixed resonators. Achieving this will require redesign of the MEMS switch structure and filter to mitigate anchor losses and metal damping.
  - We have not demonstrated a filter that switches in frequency with good Q. The new designs that are in fabrication are expected to meet this goal.

Application Potential

- **Switched / reconfigurable filters in the 10 MHz to 2 GHz range**
  - Upper frequency determined by manufacturability of switch: λ(2 GHz) ~ 4 μm
    - Higher frequencies may be achievable with longer-wavelength materials or submicron dimensions
  - Lower frequency determined by overall size of device: λ(10 MHz) ~ 800 μm
    - Other modes or approaches may allow for lower frequencies but have not been considered
- **Bandwidths of less than "a few percent"**
  - Lower bandwidth determined by Q of device
  - Upper bandwidth determined by material properties (k_t^2Q product)
  - Other materials may increase this space
- **Power levels TBD (but probably not "Watts")**

Shortcomings of Approach

- **The usual challenges associated with MEMS technologies**
  - Yield – basically two MEMS processes merged
  - Reliability – dielectric charging and metal fatigue
  - Packaging – clean hermetic microenvironment required for long-term deliverables
  - ***THESE ISSUES HAVE BEEN ADDRESSED BY CAPACITIVE SWITCH SUPPLIERS***

- **Reduced Q due to damping from switch structure**
  - Thicker metal + anchor losses presenting higher losses than standard structure
  - Switch redesign to eliminate edge crossings are expected to improve these losses
  - ***WIDER APERTURE, MORE FINGERS, ALTERNATE SWITCH DESIGN CAN IMPROVE***

- **Control complexity**
  - Control of individual fingers requires many bias lines – suggests integration with electronics for intelligence, decoding, and high-voltage drivers.
  - ***MEMS CO-INTEGRATION WITH ELECTRONICS IS IN PRODUCTION***

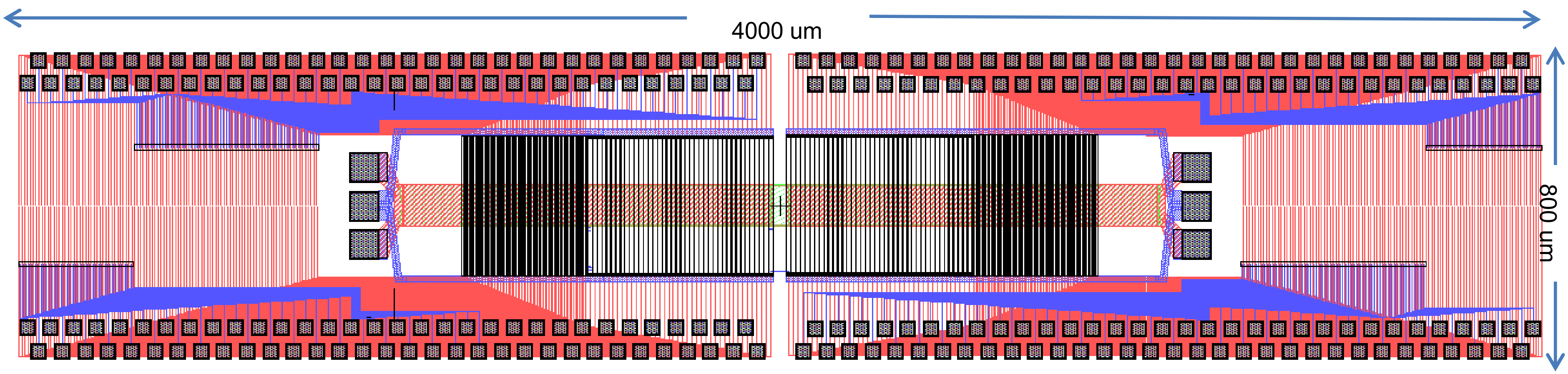
DARPA

Path To Phase Two Goals

- **Is There a Clear Path to Phase Two Goals from Where We Are?**
  - Phase Two goals: Demonstrate theater programmability of filters meeting requirements of five relevant bands.
  - The current design concepts can meet these goals, especially in conjunction with higher-Q switches
- **What Changes Do We Anticipate to the Program Plan?**
  - Accelerated integration of the MEMS switch with the resonator from Stage II into Stage I at DARPA's request – did not pursue fixed filters as a result
  - Expect focus of Stage II to shift towards modeling and testing to improve the Q and response of the filters.

Next Steps

- **Stage I (through 9/12/2013)**
  - Complete current wafer lot (new designs)
  - Preliminary testing of devices on new wafer lot
- **Stage II Goal: Real-time programmable filter covering five states**
  - Exhaustive testing of new designs and matching to models
  - Improve Q and filter responses
  - Two fabrication and test cycles anticipated



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Summary

- **Demonstrated piezoelectric switching using MEMS switches**
  - Appears there are no fundamental flaws with this approach
- **Demonstrated integrated MEMS resonator + MEMS switch process flow**
  - Capacitive switches may also allow EM filter tuning, switching, and impedance matching
- **Demonstrated on/off switched single resonators at frequencies from 120 MHz to 480 MHz with Q's up to 300+**
  - Key effort in Stage II will be improving the Q and filter performance
- **Modeled filter structures and identified key parameters for transducer and reflector fingers**
  - Applied learning to designs that are still in fabrication
- **This approach is viable for introducing reconfigurability to piezoelectric resonators and filters**