SAND2007-3323C

MICROMACHINED BULK WAVE ACOUSTIC BANDGAP DEVICES

14th International Conference on Solid-State Sensors, Actuators, and Microsystems

June 12th 2007

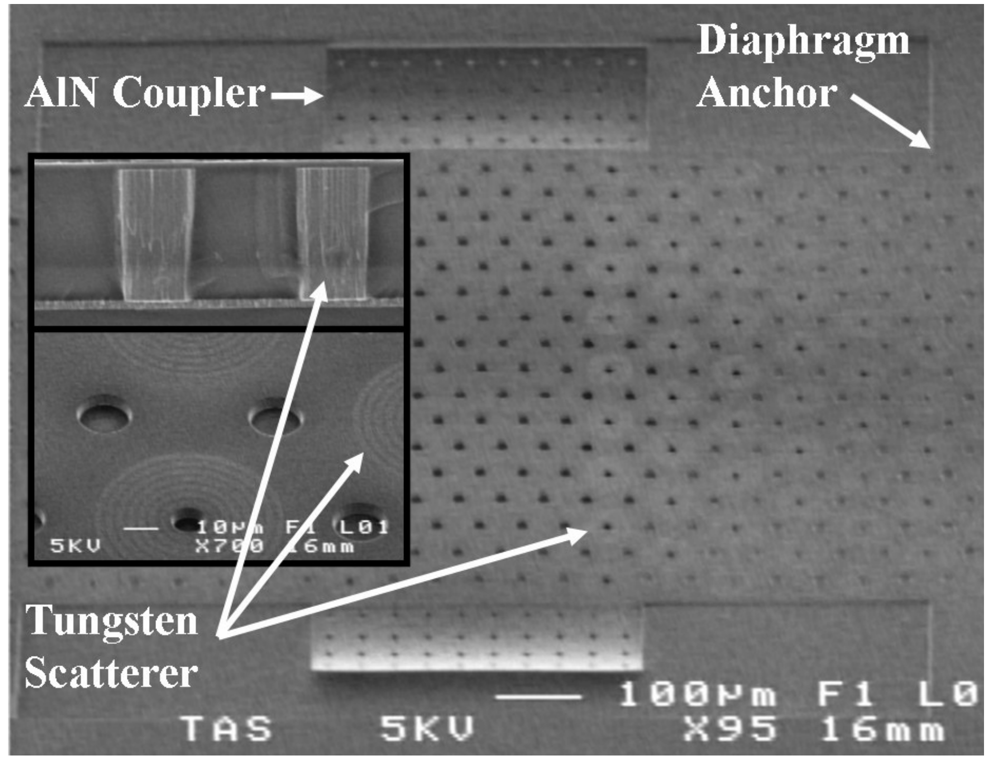
Roy H. Olsson III, James G. Fleming, Ihab F. El-Kady, Melanie R. Tuck, and Frederick B. McCormick

Senior Member of Technical Staff
Sandia National Laboratories

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Outline

- Background
  - What is an acoustic bandgap (ABG) device or acoustic crystal?
- Design
  - Materials
  - Topology
  - Couplers
- Fabrication
- Measured Results
- Acoustic Bandgap Waveguides
- Applications and Future Directions



Triangular lattice ABG waveguide operating at 30 MHz

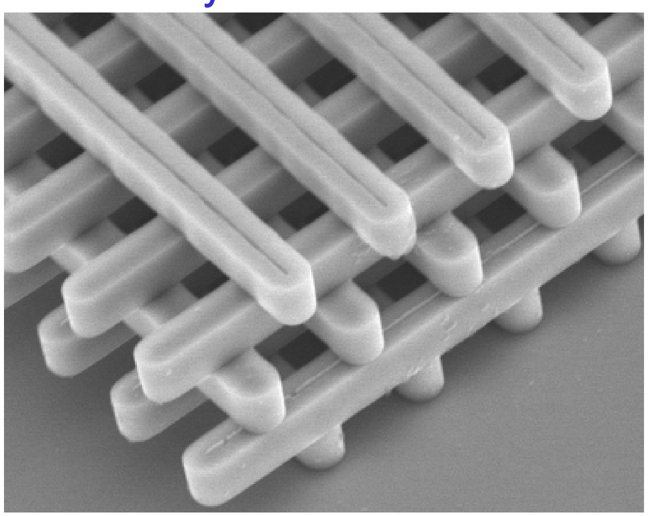
Acoustic vs. Photonic Crystals

Photonic Bandgap (PBG)

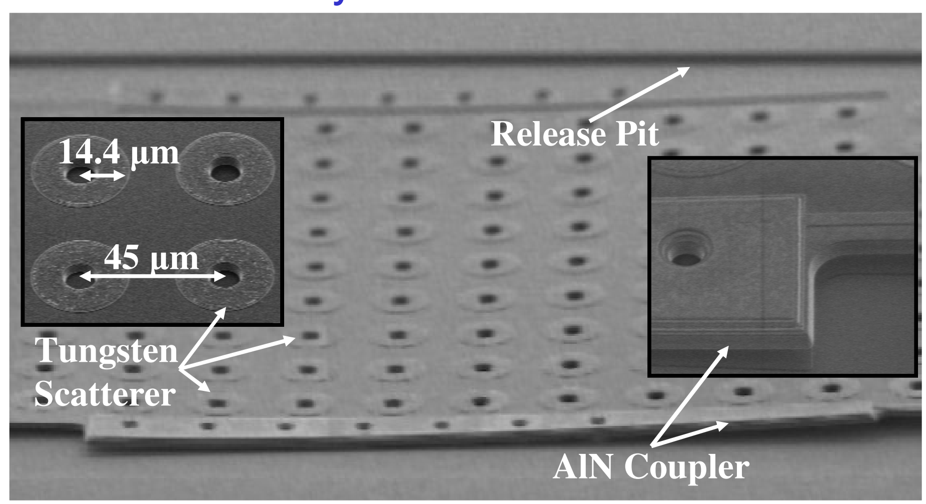
- High refractive index scatterer in low refractive index matrix
- Network topology
- 3D required for full control
- Integration of lasers and photodetectors problematic
- 2^{nd} order coupled vector equations with 2 polarizations
- Inherently linear

Acoustic Bandgap (ABG)

- High acoustic impedance scatterer in low acoustic impedance matrix
- Cermet topology
- Full control in 2D (vacuum)
- Micromachined integration of piezoelectric or capacitive couplers
- 2^{nd} order coupled vector equations with 3 polarizations
- Inherently non-linear



3D woodpile photonic crystal



2D acoustic crystal

Sandia National Laboratories

ABG Materials Selection

Matrix

- Low acoustic impedance
- Low density
- High velocity
- High-Q

Matrix Material	Density (kg/m^3)	Velocity (km/s)	Z (MΩ)	Q
Polymers	1190	1.84	2.2	≈ 10^2
AlN	3230	9.77	31.5	> 10^3
Si	2330	8.52	19.8	> 10^5
SiO_2	2200	5.84	12.8	> 10^3

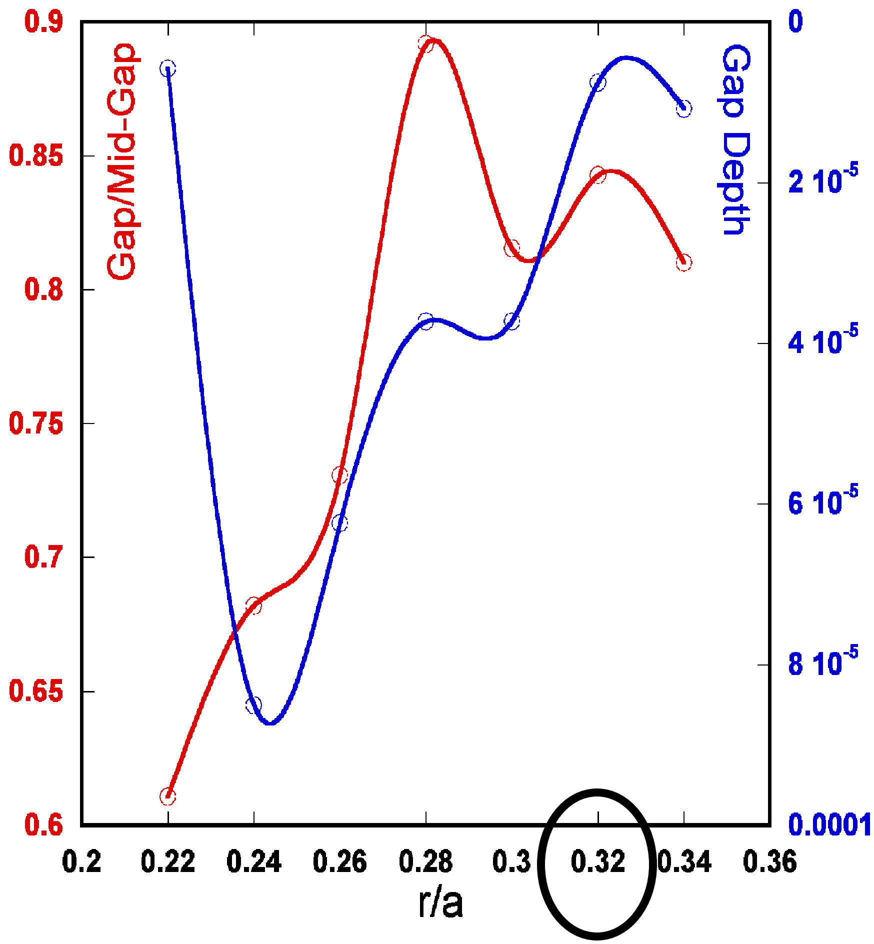
Inclusion

- High acoustic impedance
- High density
- High velocity
- High-Q

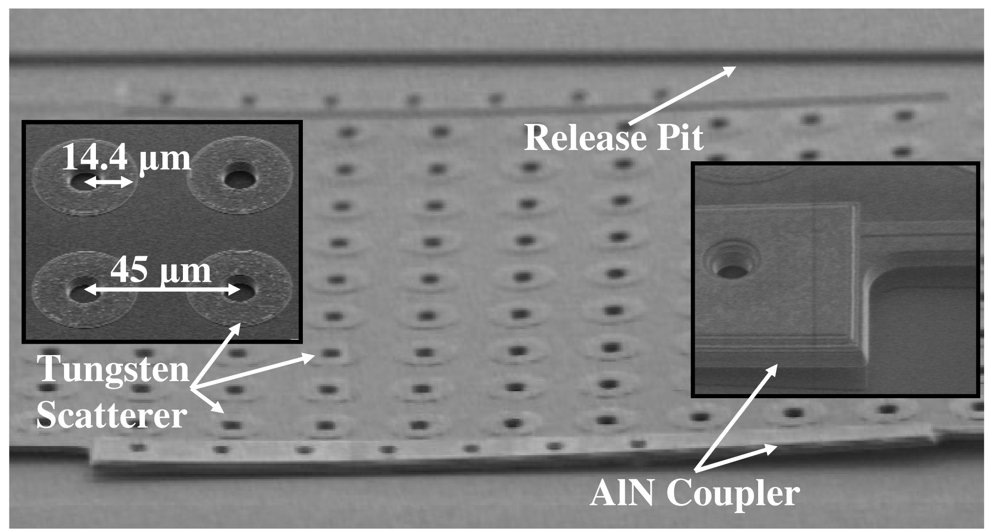
Inclusion Material	Density (kg/m^3)	Velocity (km/s)	Z (MΩ)	Q
Moly	10,300	5.7	59	> 10^5
Pt	21,440	2.8	60	> 10^4
W Carbide	15,800	6.6	104	?
W	19,300	4.6	89	> 10^5

Sandia National Laboratories

Fabrication at Higher Frequency



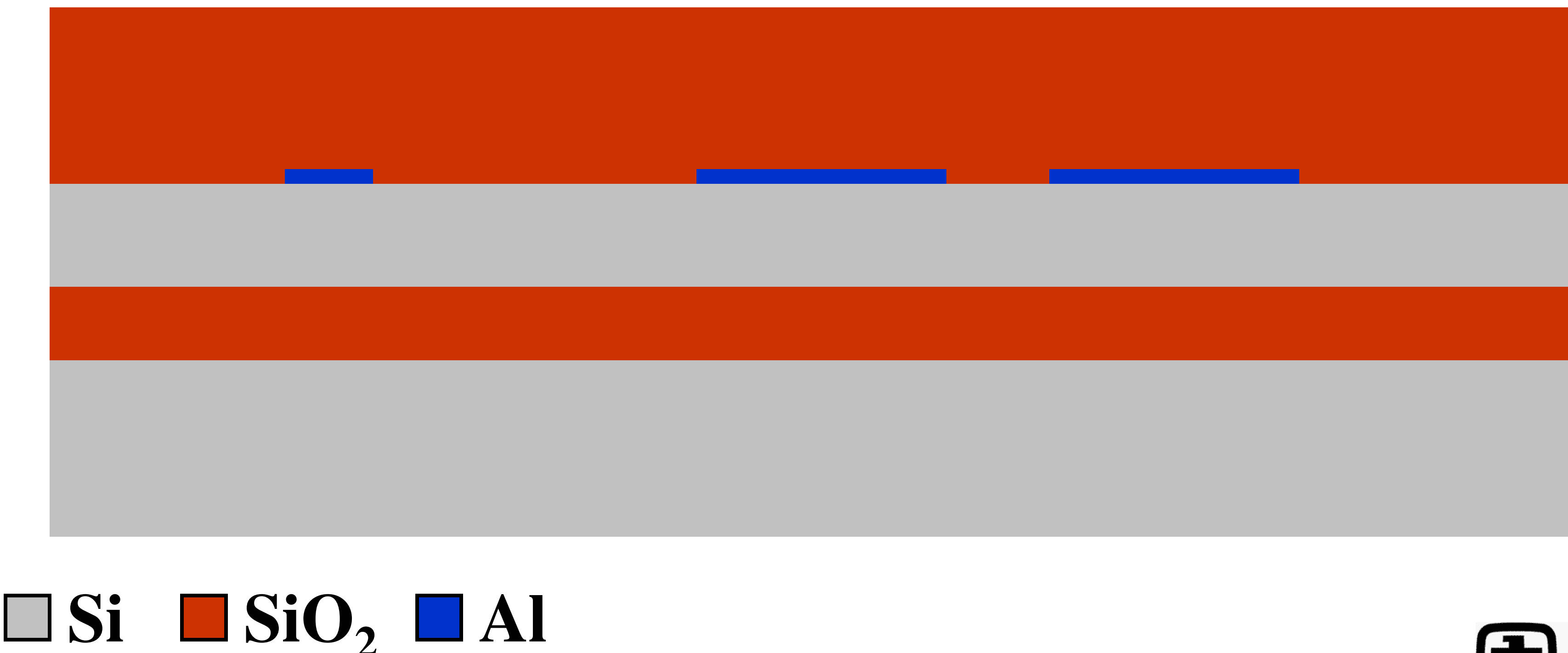
Frequency (MHz)	Lattice Constant ***a*** (μm)	W Radius ***r*** (μm)
30 MHz	100 μm	32
67 MHz	45 μm	14.4
300 MHz	10 μm	3.2
3 GHz	1 μm	0.32



Sandia National Laboratories

ABG Fabrication

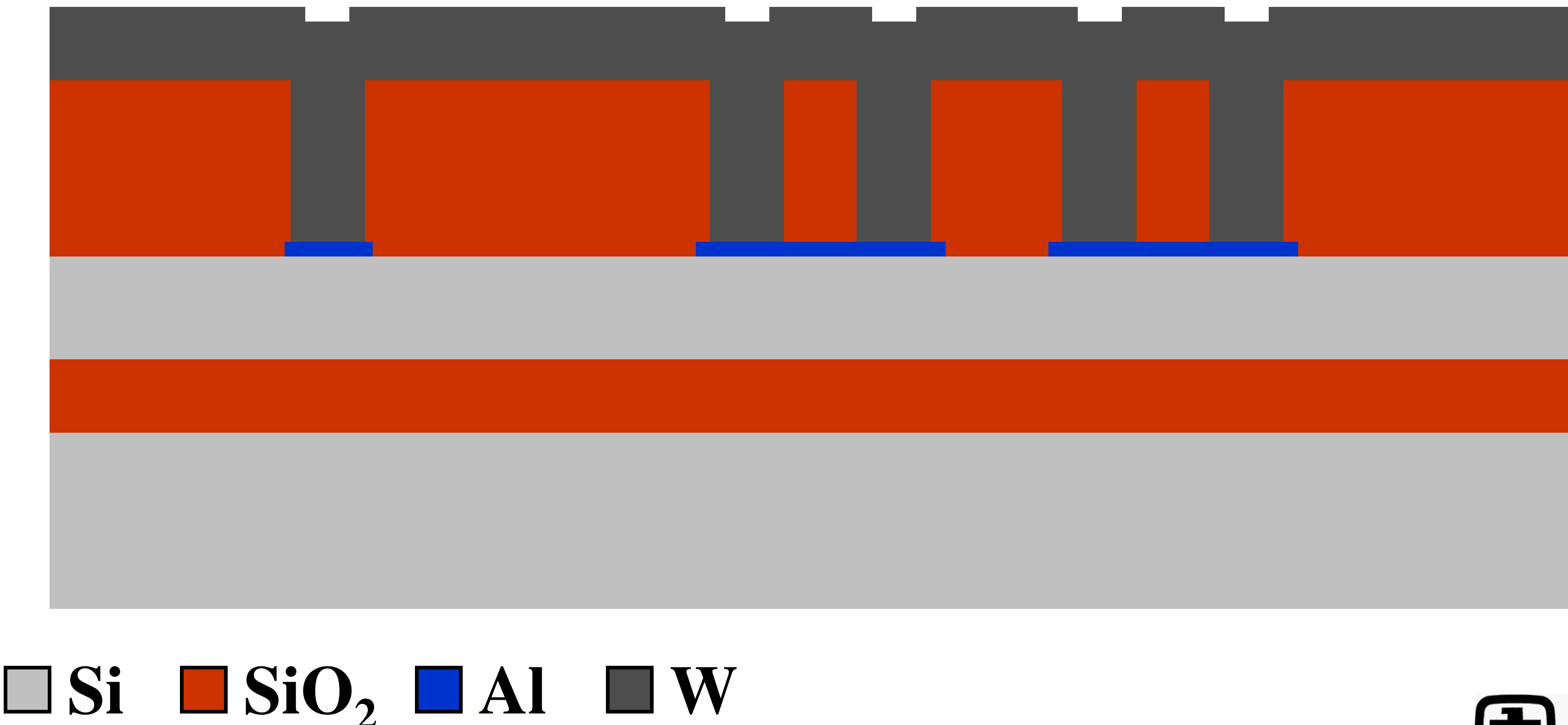
- Deposit oxide etch-stop and silicon release layers
- Sputter deposit and pattern Al bottom interconnect layer
- PECVD SiO_2 low density, low impedance matrix material



Sandia National Laboratories

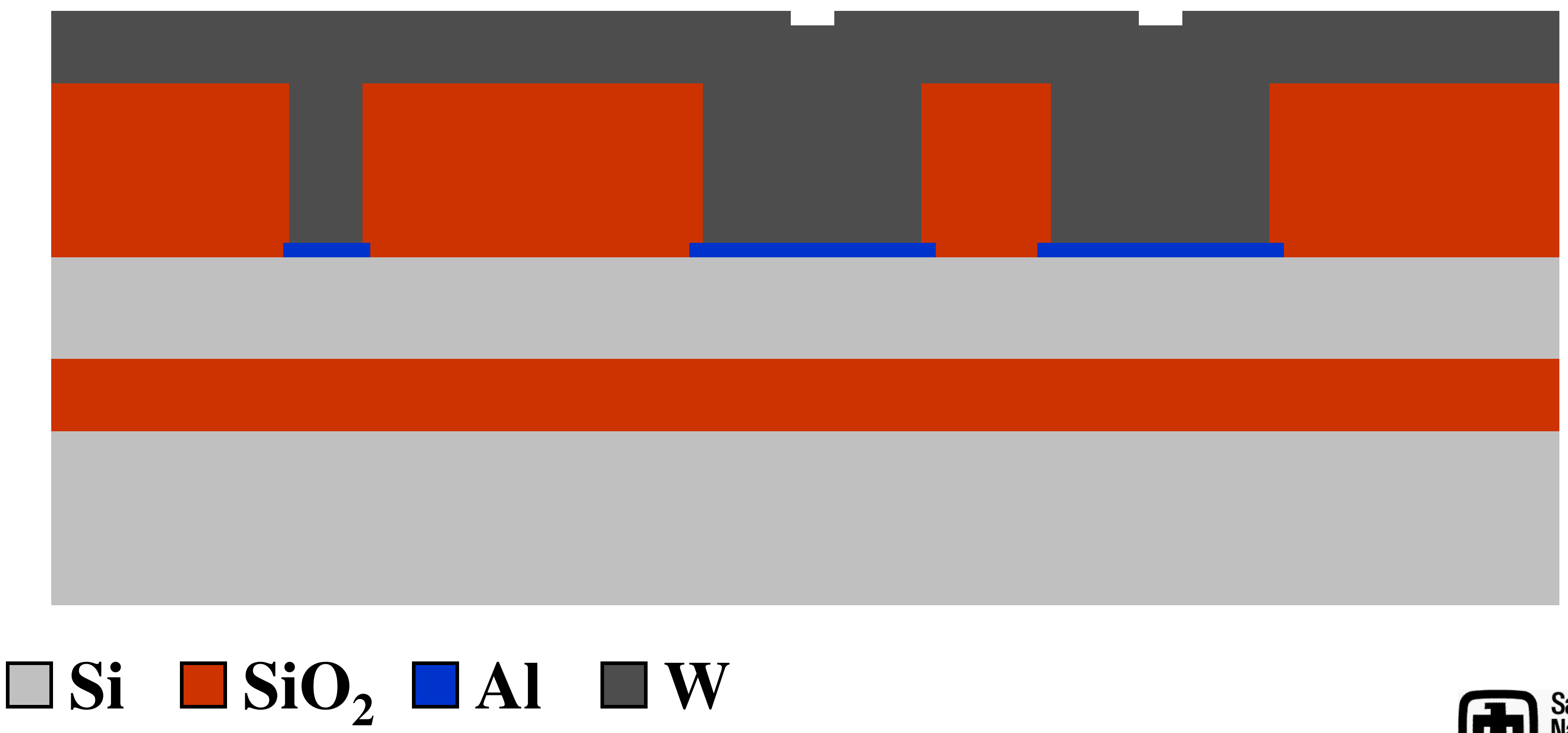
ABG Fabrication

- Etch holes in the oxide for scatterer formation, stop on Al
- CVD 1.2 µm of Tungsten (W)
- CMP Tungsten until it remains only in the etched oxide holes



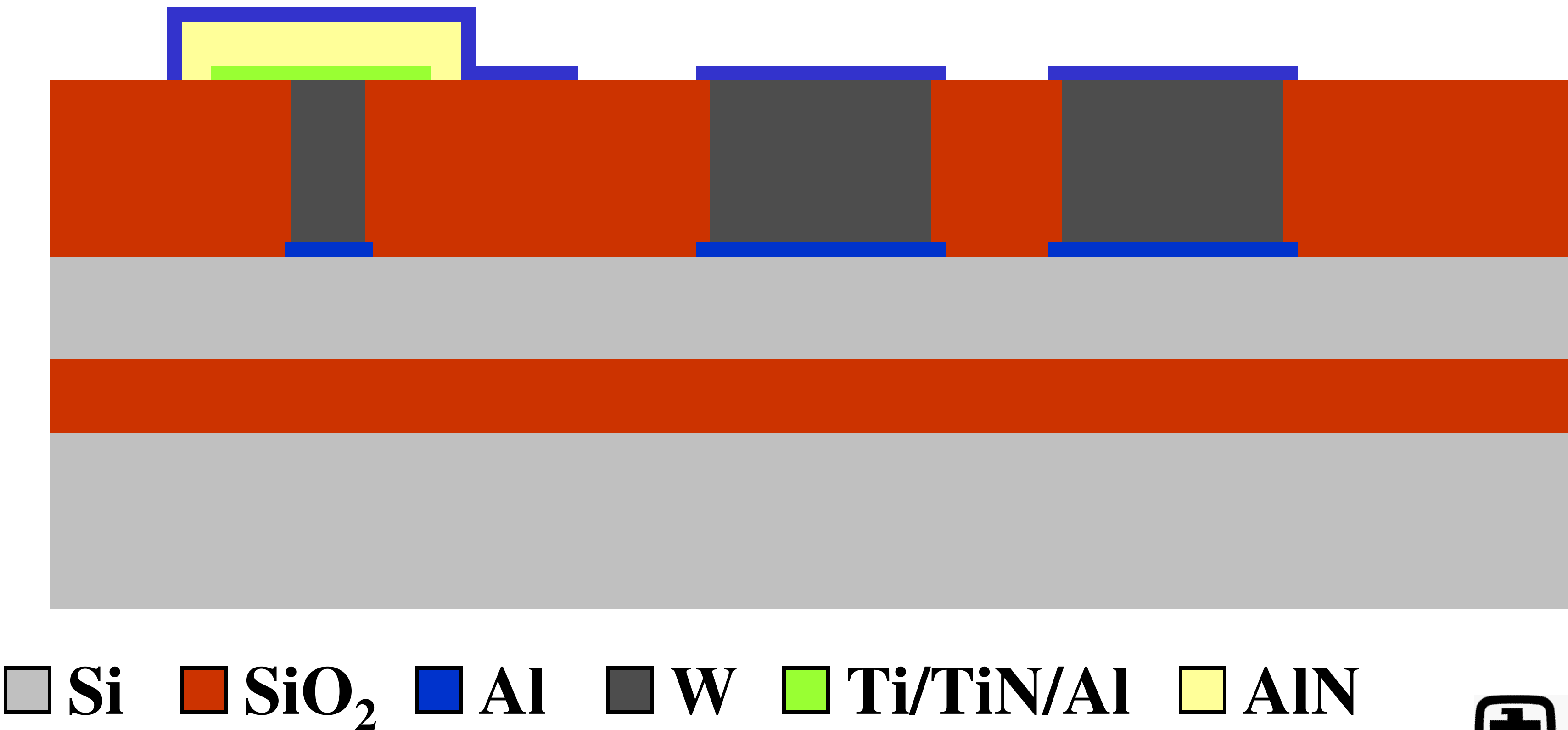
ABG Fabrication

- Etch holes in the oxide to complete the scatterer
- CVD 1.2 µm of Tungsten (W)
- Tungsten CMP



ABG Fabrication

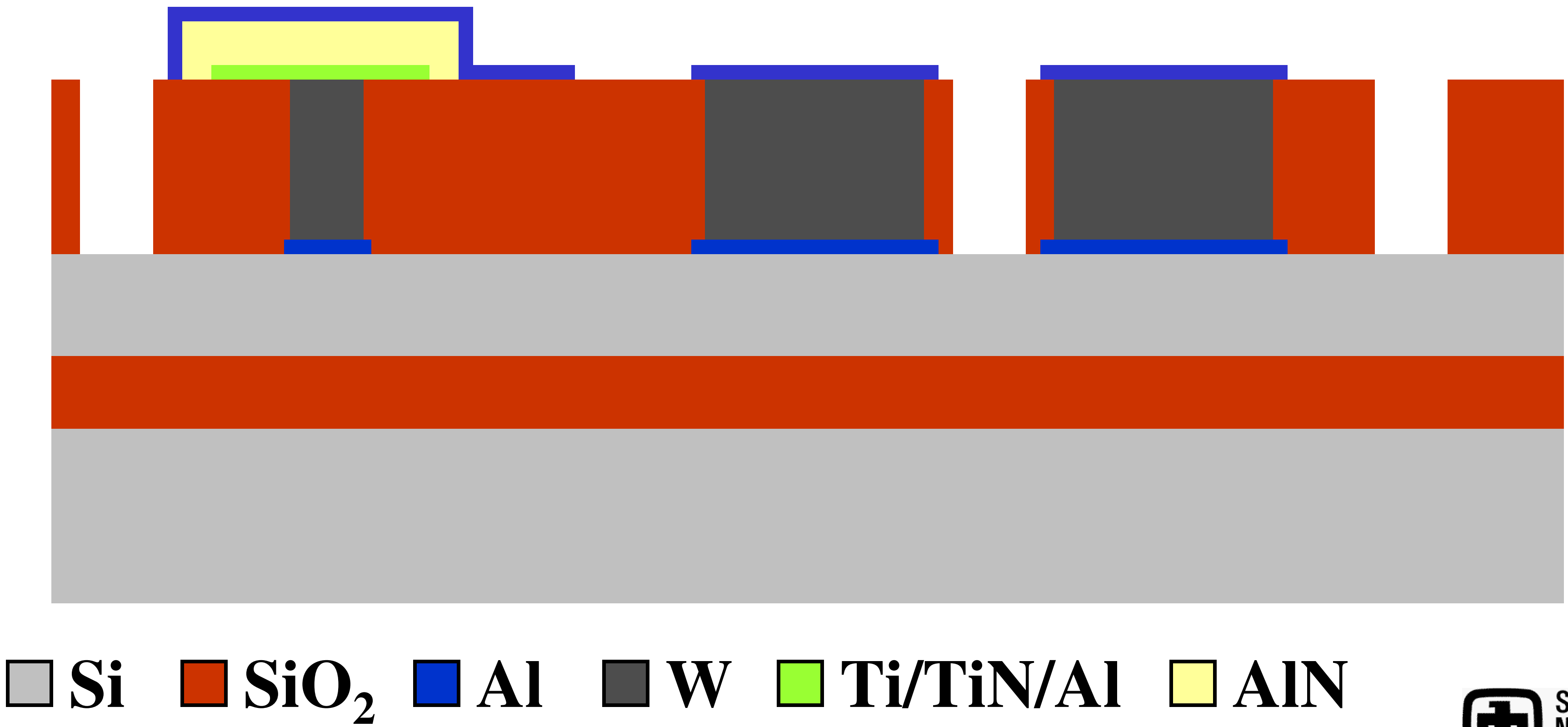
- Deposit and pattern Ti/TiN/Al bottom electrode (FWHM = 1.5°)
- Sputter deposit and pattern 0.75 μm AlN at 350 °C
- Deposit and pattern top Al electrode



Sandia National Laboratories

ABG Fabrication

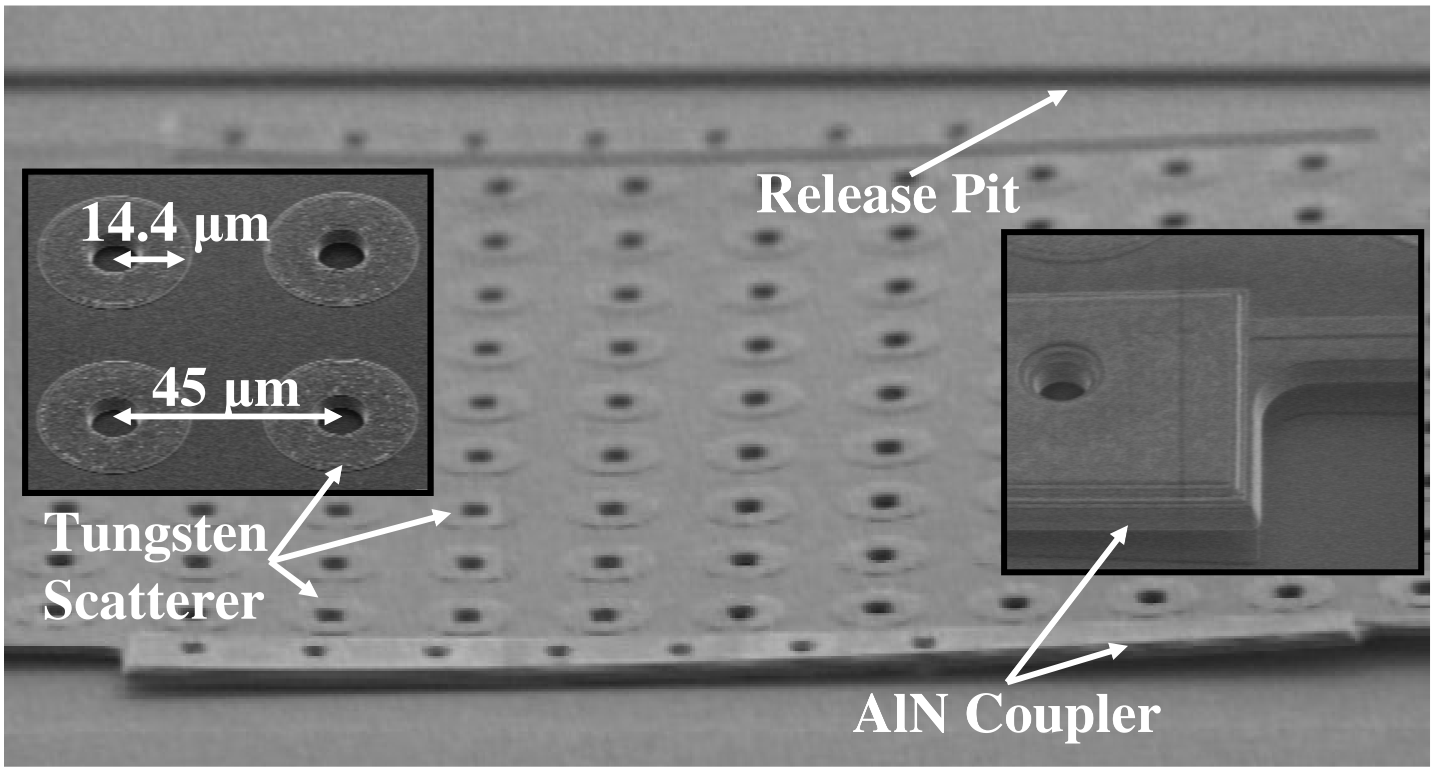
- Etch release holes through oxide to Si release layer
- Release in dry SF_6



Sandia National Laboratories

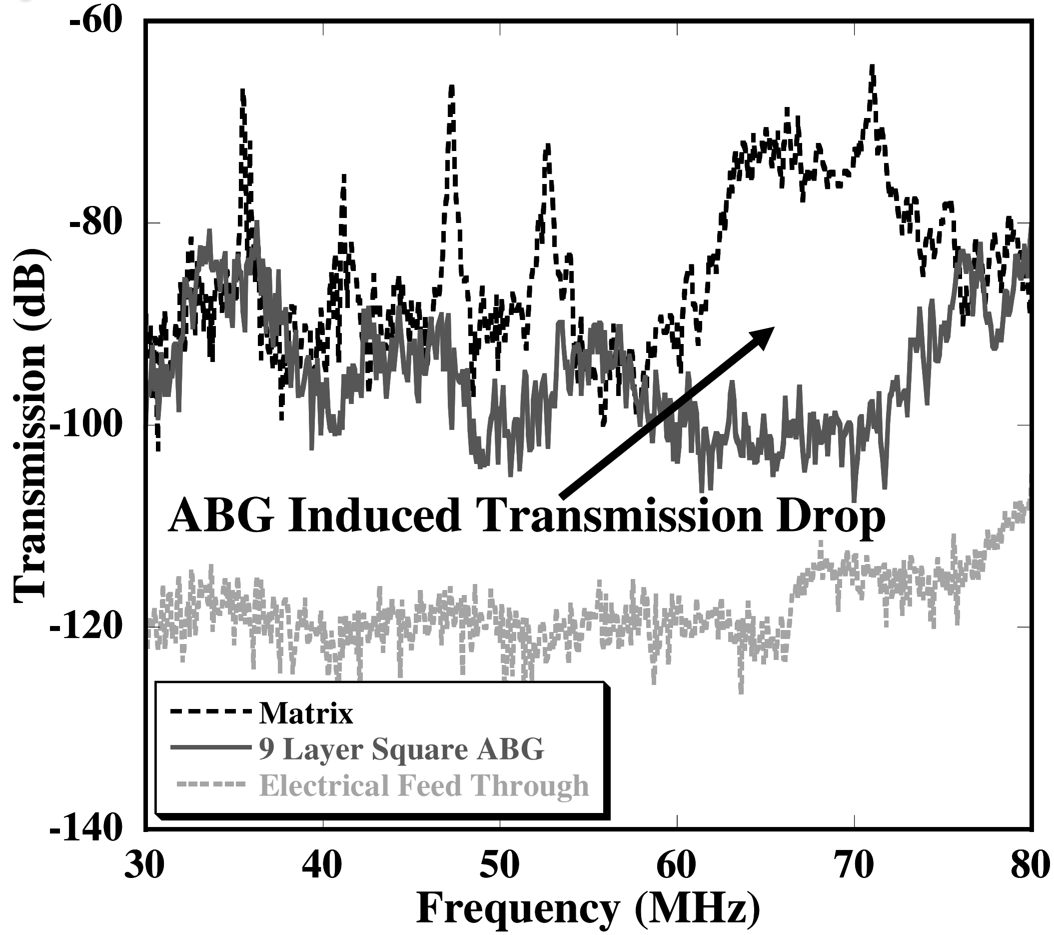
ABG Fabrication

- 7 Levels (Post-CMOS Compatible)
- Tungsten (ρ = 19,300 kg/m^3, Z = 89 MΩ)
- SiO_2 (ρ = 2,200 kg/m^3, Z = 13 MΩ)
- Merged AlN and molded W processing

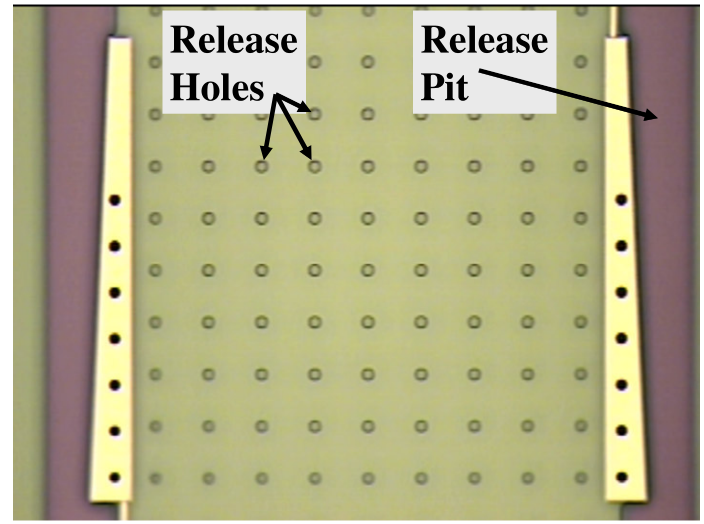


ABG with integrated AlN electro-acoustic couplers centered at 67 MHz

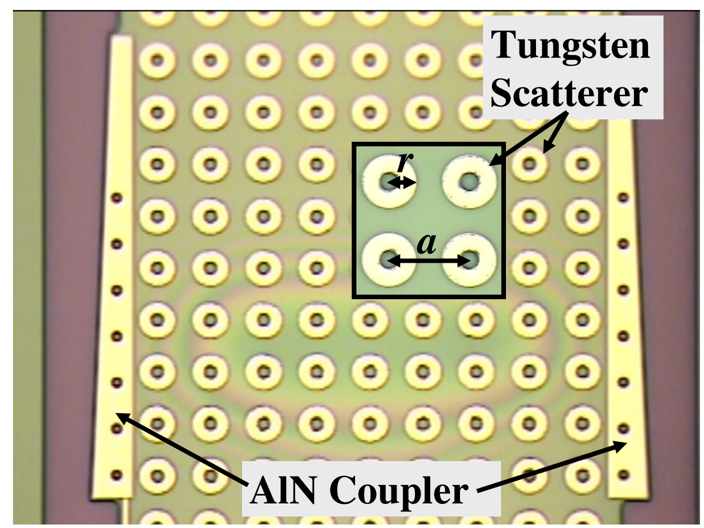
ABG Measured Results



Measured transmission of the reference matrix membrane, 9-layer square lattice ABG, and the feed-through between two acoustically uncoupled pads



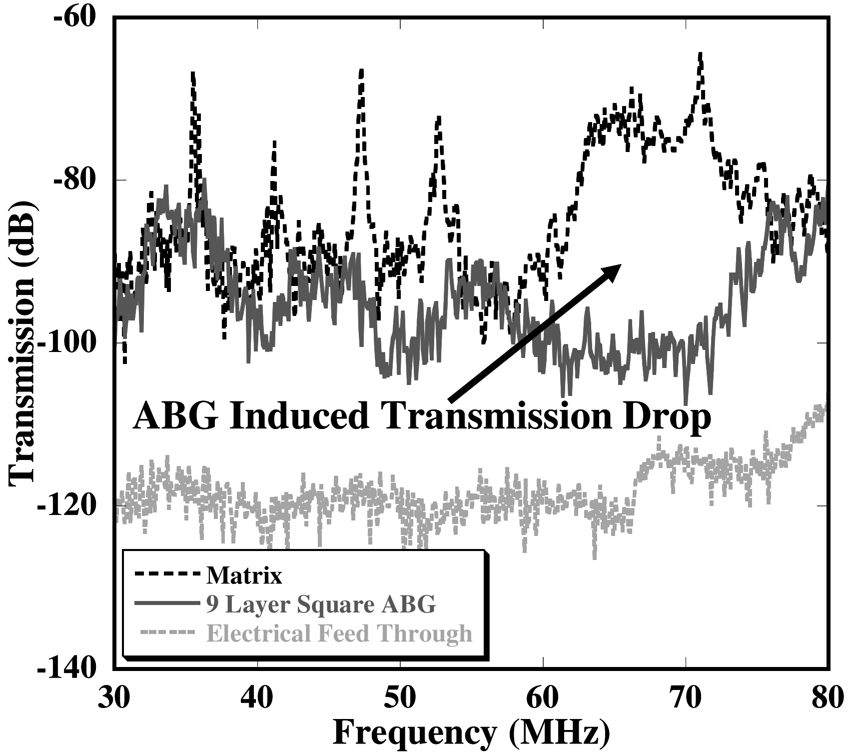
SiO_2 matrix with AlN couplers

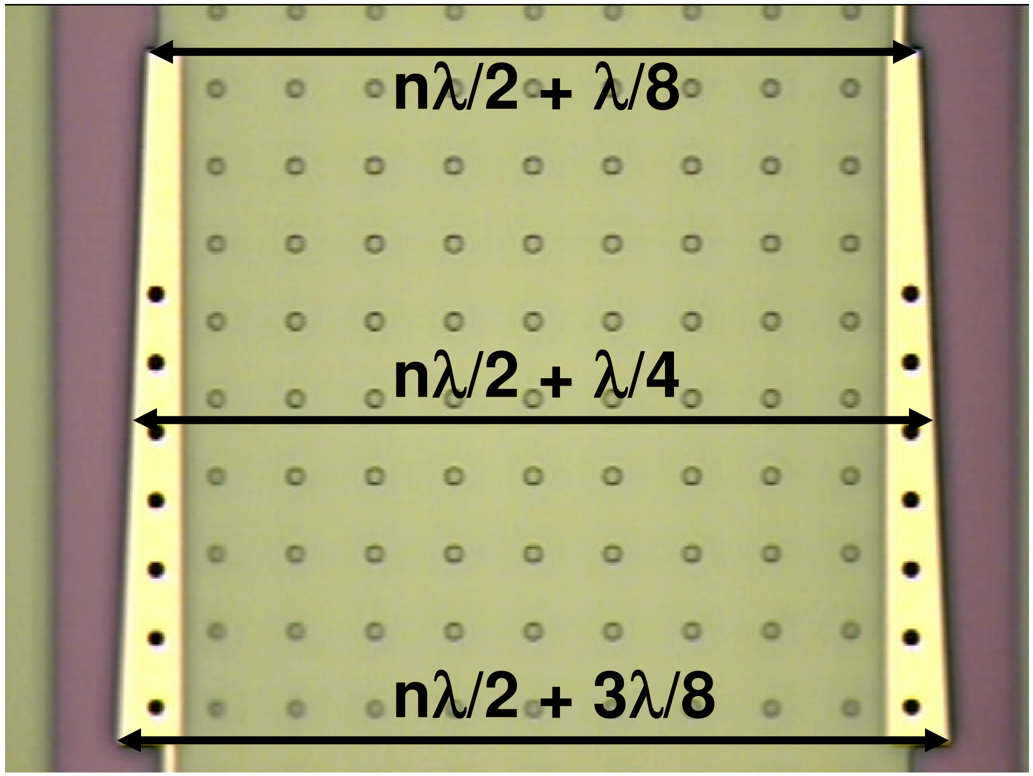


Square lattice ABG

Sandia National Laboratories

ABG Wideband Coupler Design





$C_{oxide} = 5.8\ km/s$

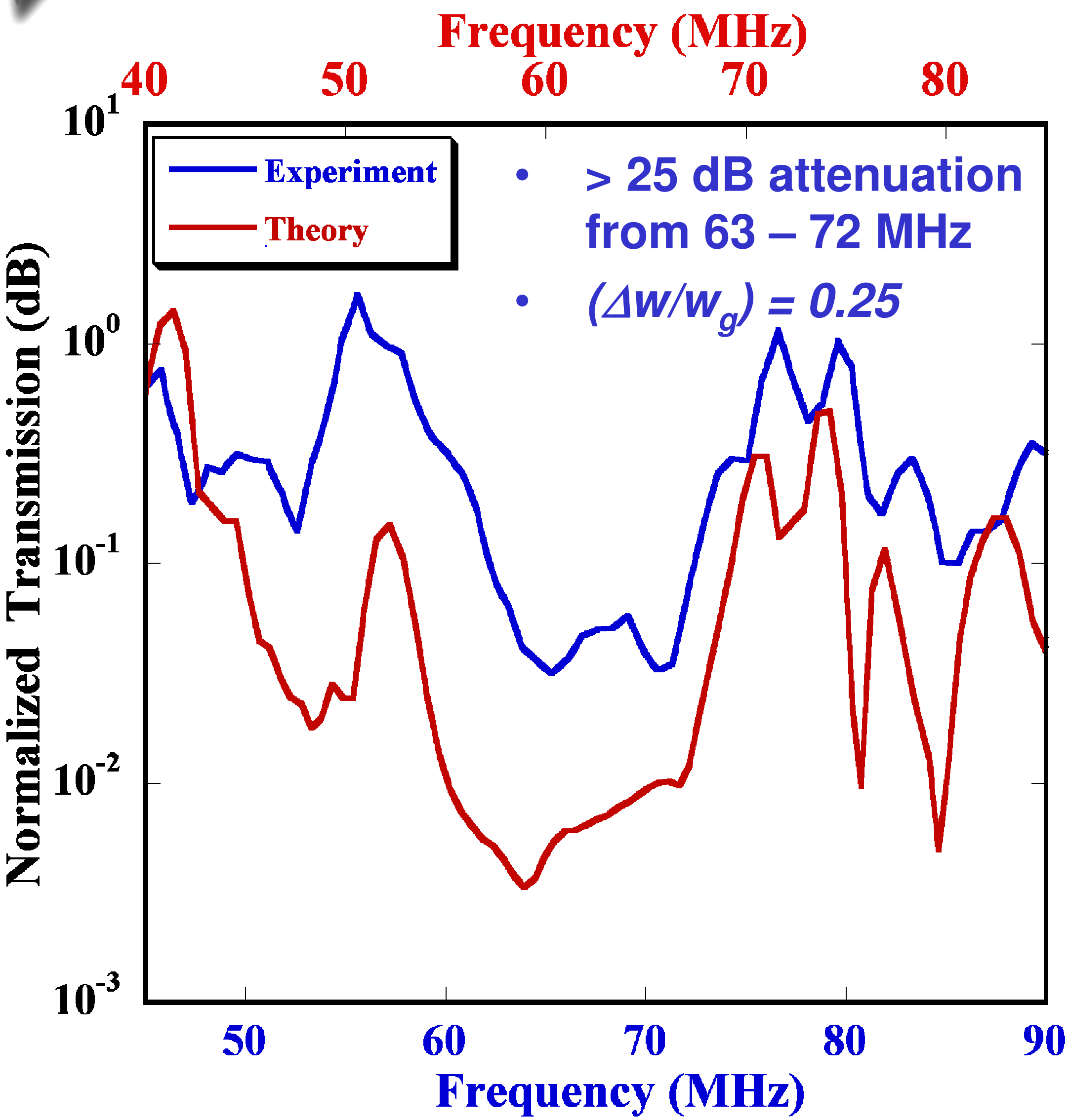
$n = 10$

$\lambda = 88\ \mu m$

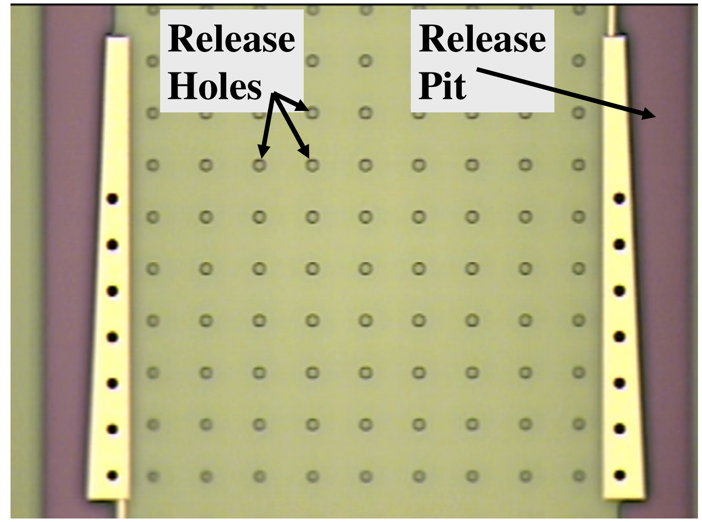
$f_0 = 66\ MHz$

Sandia National Laboratories

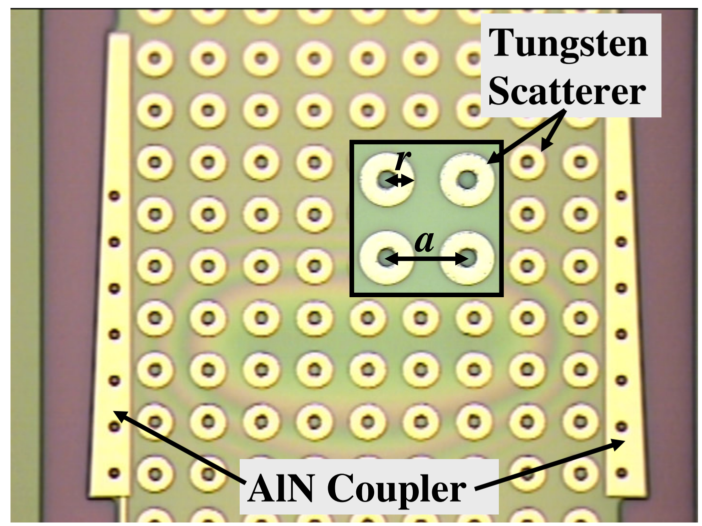
ABG Normalized Transmission



FDTD simulated and measured relative transmission for the square lattice ABG



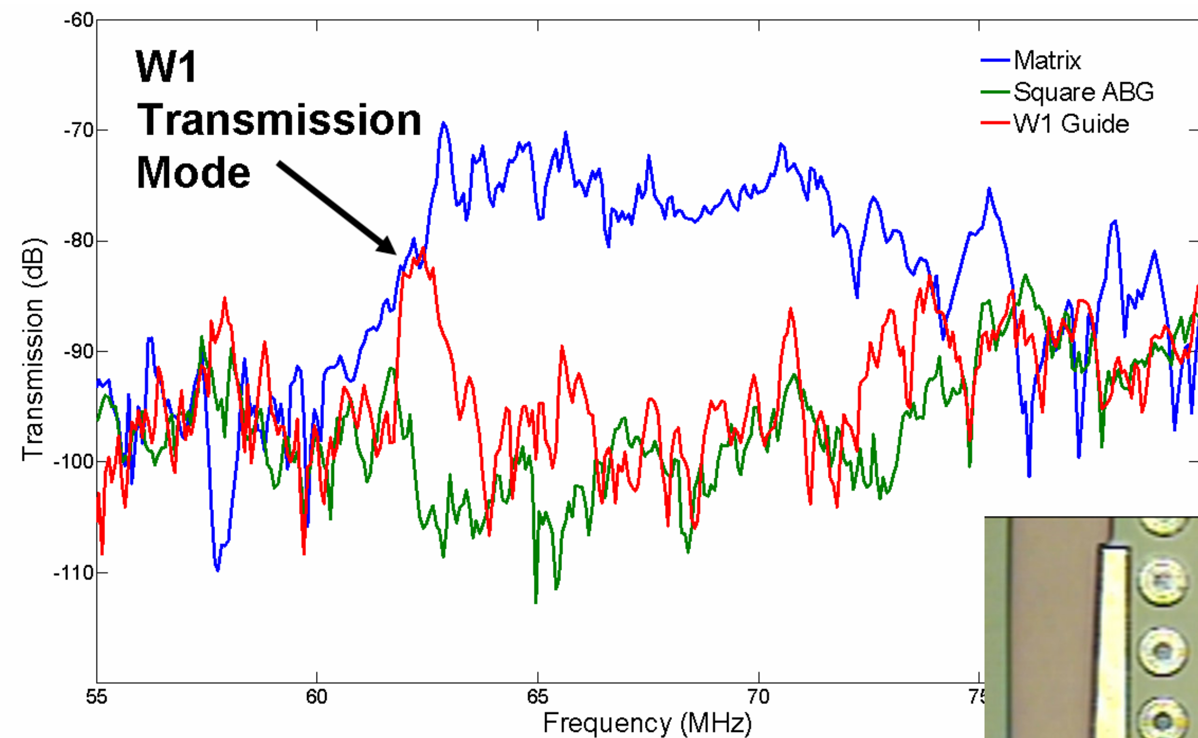
SiO_2 matrix with AlN couplers



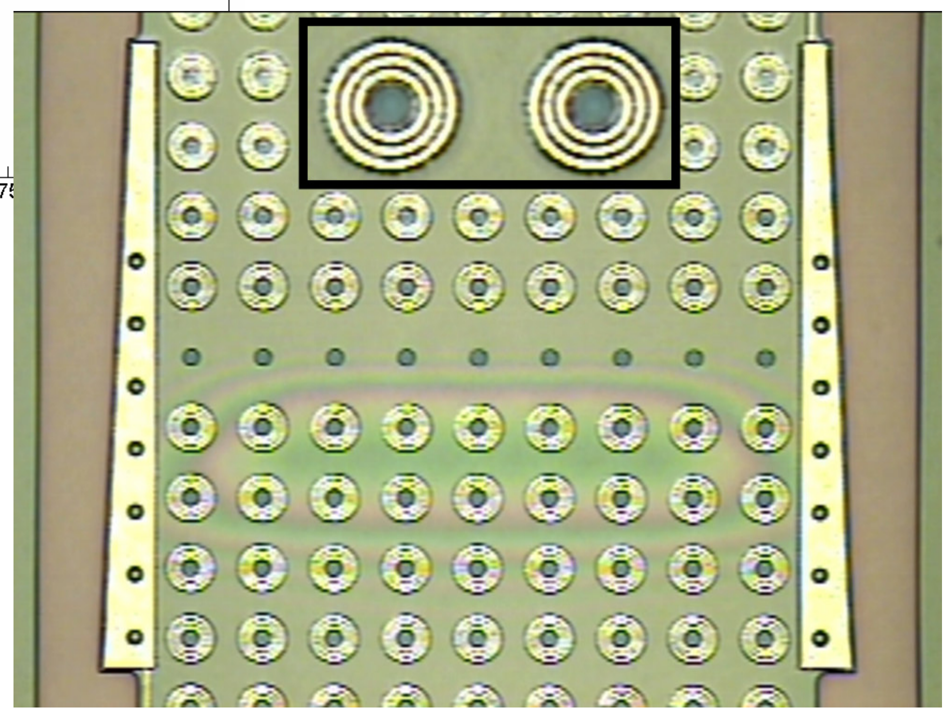
Square lattice ABG

Sandia National Laboratories

ABG W1 Waveguide

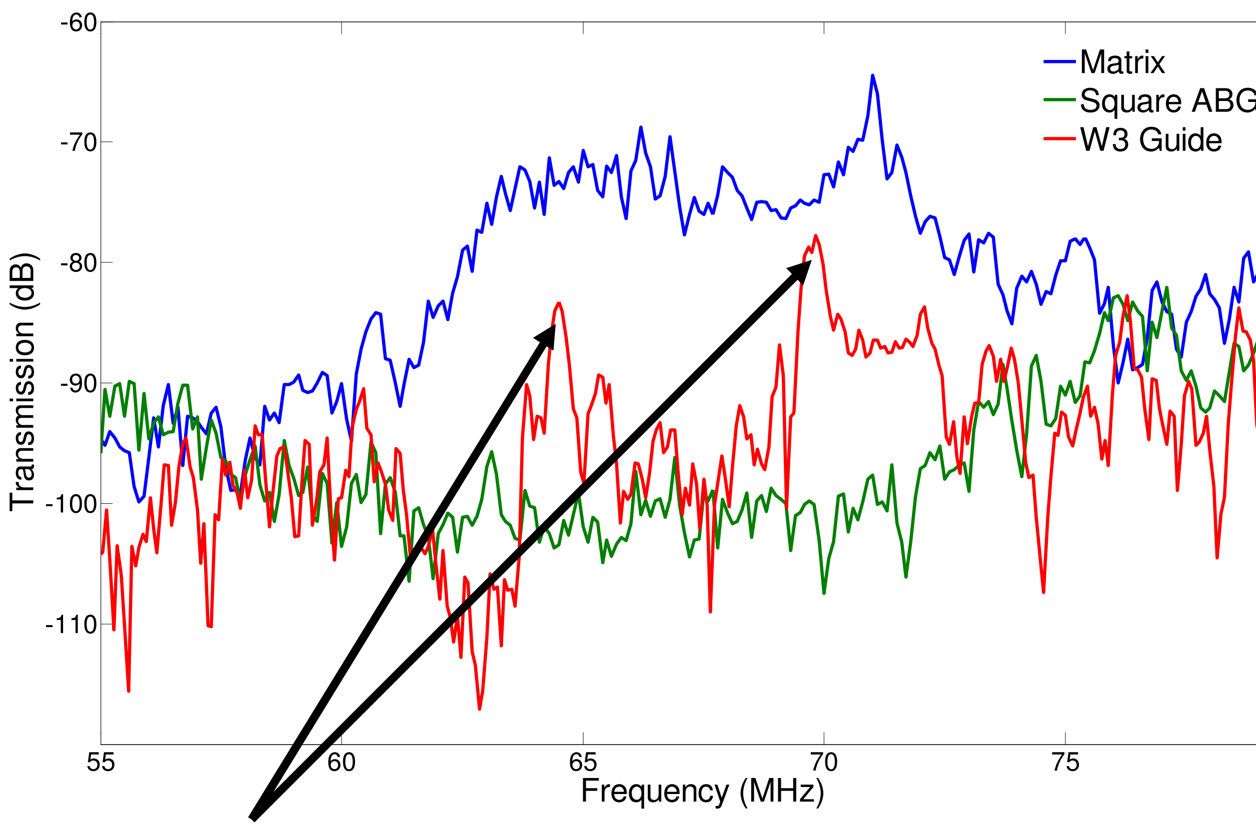


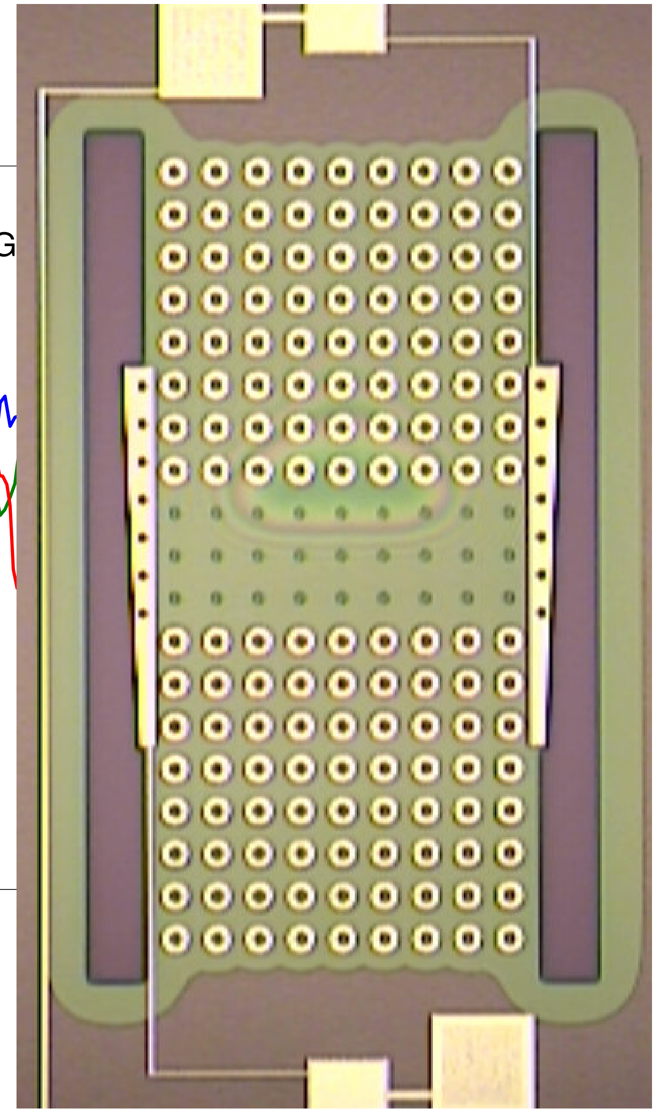
(Left) Measured response of a W1 waveguide showing 100% relative transmission at 62 MHz



(Right) Picture of an ABG W1 waveguide where 1 row of tungsten scatterers has been removed between the AlN couplers

ABG W3 Waveguide

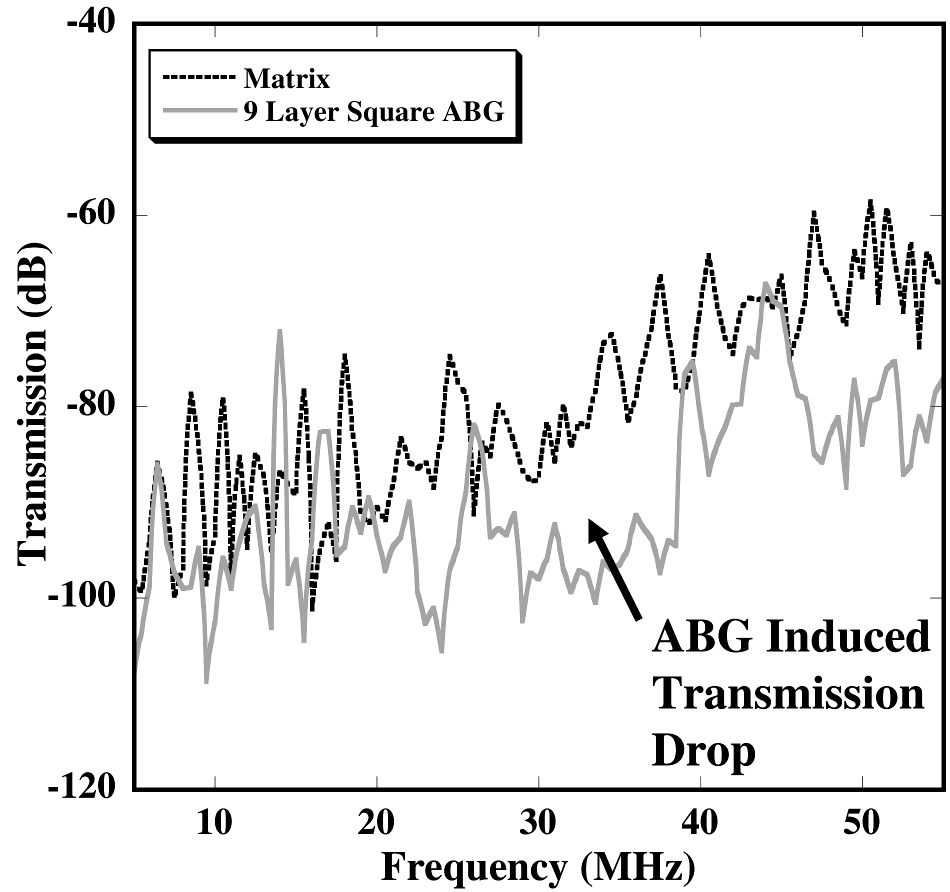




Modes Propagating in the Guide

Potential Applications

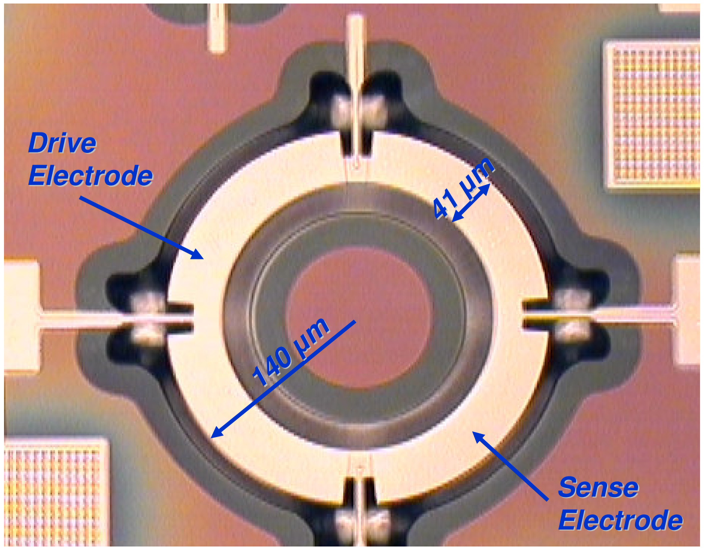
- RF
  - High-Q Cavities
  - High Order Filters
  - Nonlinear Devices
- Bio
  - Cell Manipulation
  - Mass Sensing
- Ultrasound
  - Acoustic Focusing
- Nondestructive Testing
  - Acoustic Focusing
  - Crack Detection

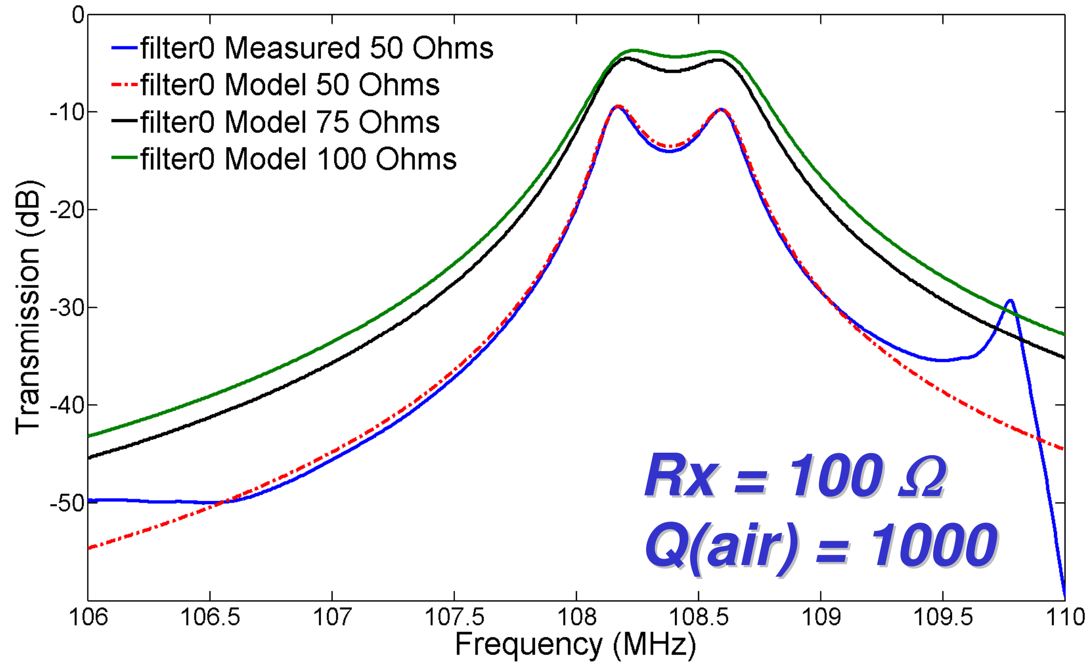


Transmission of a 33 MHz ABG

High-Q Cavities (Piezoelectric Devices)

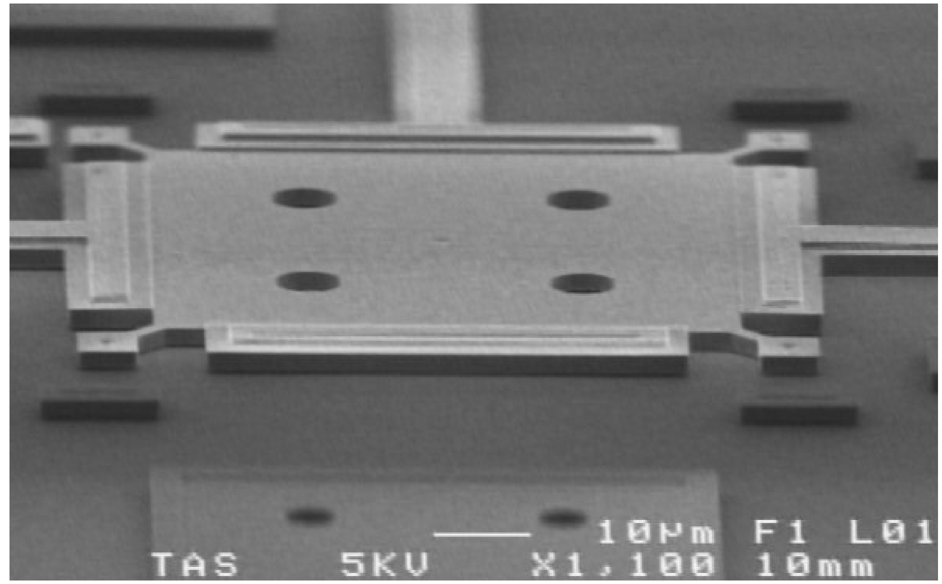
- Low insertion loss (impedance) filters because of the strong piezoelectric transduction
- Resonator is comprised of piezoelectric material
- Material damping limits Q to a few thousand
- Devices include SAW, FBAR, and AlN microresonator

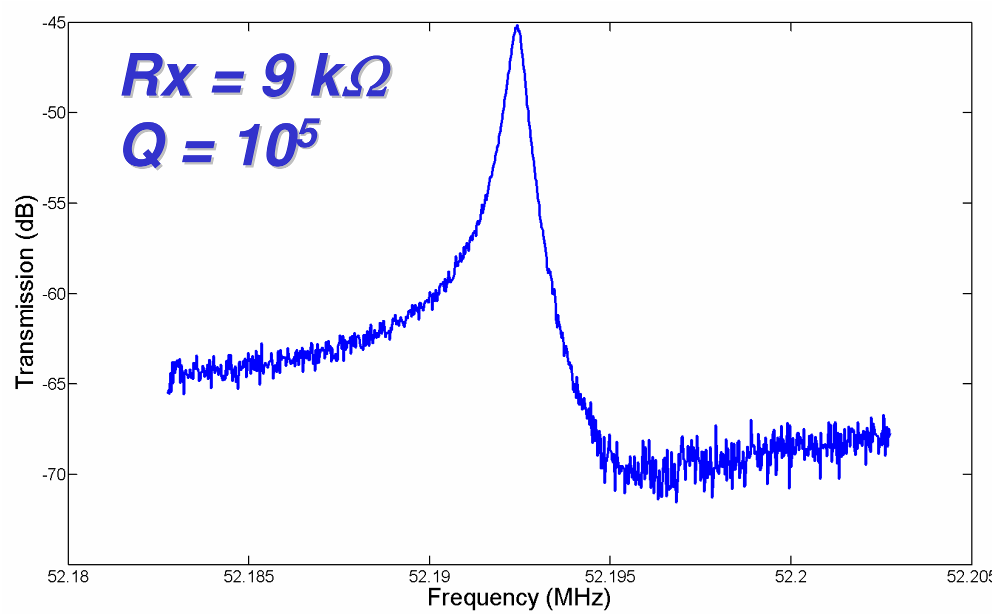




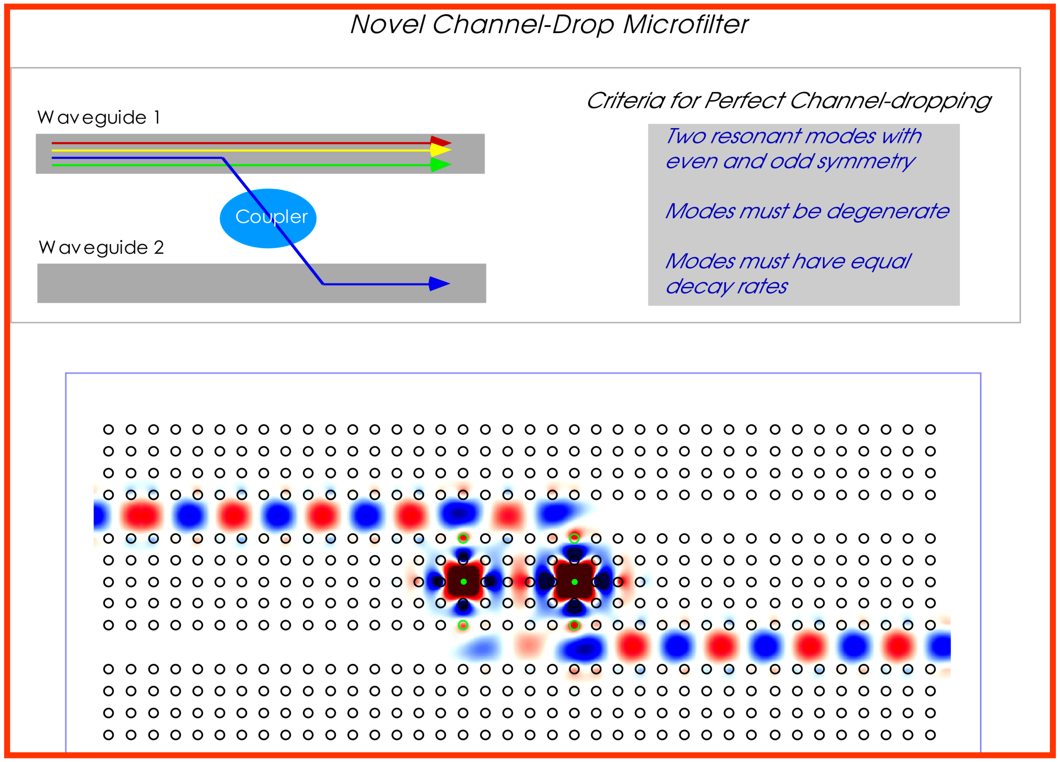
High-Q Cavities (Silicon Devices)

- High-Q derived from low material damping polysilicon
- Q's of a few 100,000 possible
- 2 orders of magnitude higher than piezoelectric materials
- High insertion loss (impedance) due to weak capacitive transduction
- Devices include polySi, SiGe, Ni and W microresonators

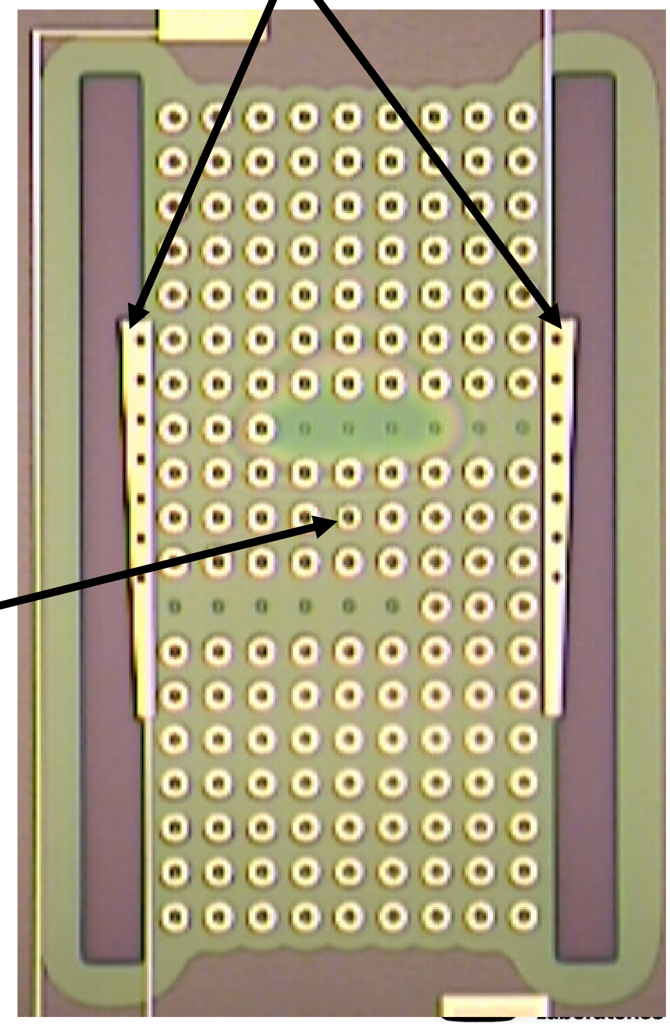




High-Q Cavities (ABG Devices)



Piezoelectric Couplers (low insertion loss)

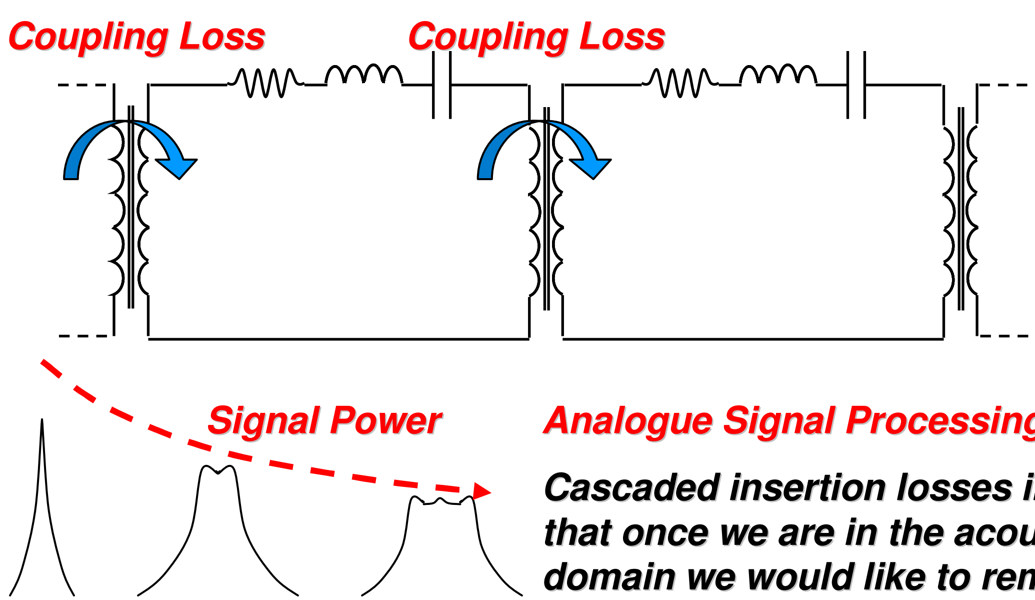


Cavity realized in High-Q ABG materials

- Cavities with $Q > 10^6$ reported for photonic crystals by altering ABG pitch (easier to control lithographically)

ABG for High-Order Filters

- Insertion loss is dominated by coupling from EM to acoustics
  - Once in the acoustic domain would like to stay there
- High order filters by mechanically or electrically coupling resonators
- FBAR can not achieve mechanical coupling » must electrically couple
- Mechanically coupled microresonators
  - Coupled by small beams requiring order of magnitude better lithographic control than the resonators themselves
  - Bandwidth and ripple hard to control » practical devices are electrically coupled



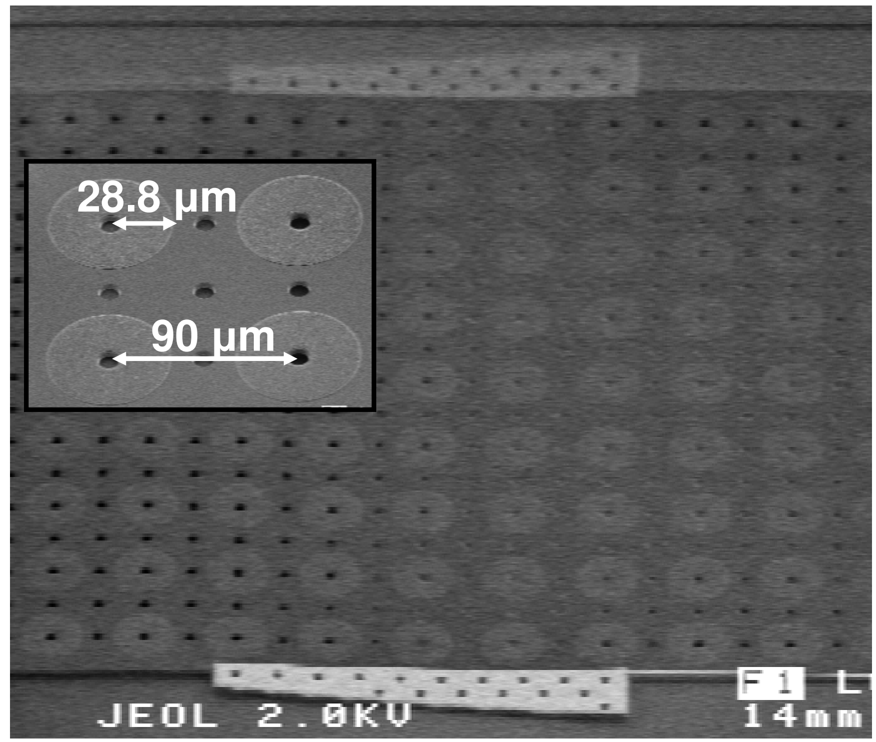
Analogue Signal Processing:

Cascaded insertion losses imply that once we are in the acoustic domain we would like to remain in it!

- ABG allows resonators to be coupled by waveguides
- Cavities realized by altering pitch
- High order, low loss filters and advanced signal processing

Conclusions

- Described Acoustic Bandgap Devices (ABGs)
- Design of ABGs
  - Materials, Topology, Couplers
- Fabrication
  - Post CMOS compatible AlN and W process
- Measured Results
  - > 25 dB ABG over ≈ 10 MHz @ 70 MHz
- Acoustic Bandgap Waveguides
  - W1 and W3 single and multi-mode waveguides
- Applications
  - RF, Bio, Ultrasound Nondestructive Testing



Square lattice ABG operating at 30 MHz

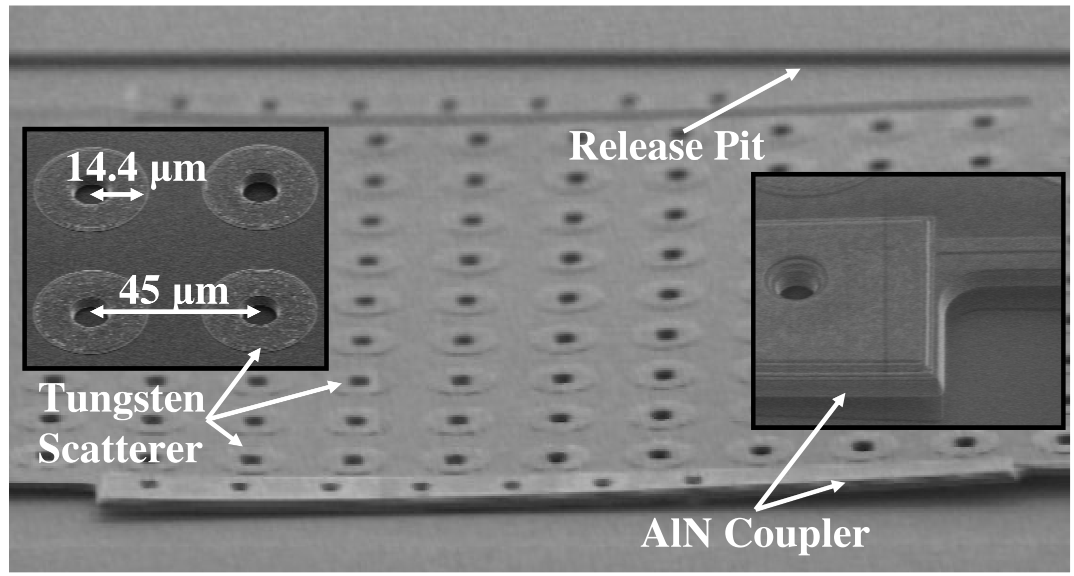
Acknowledgments

Acknowledgement

Microelectronics Development Laboratory Staff at Sandia National Laboratories

Special Acknowledgement and Remembrance

To our late colleague and Co-author James (Jim) Fleming.



Contact Information

Roy Olsson (rholsso@sandia.gov)

Sandia National Laboratories