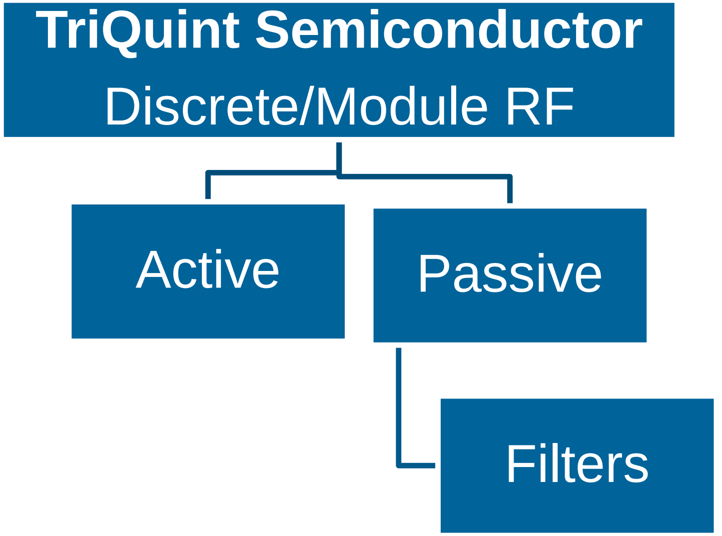
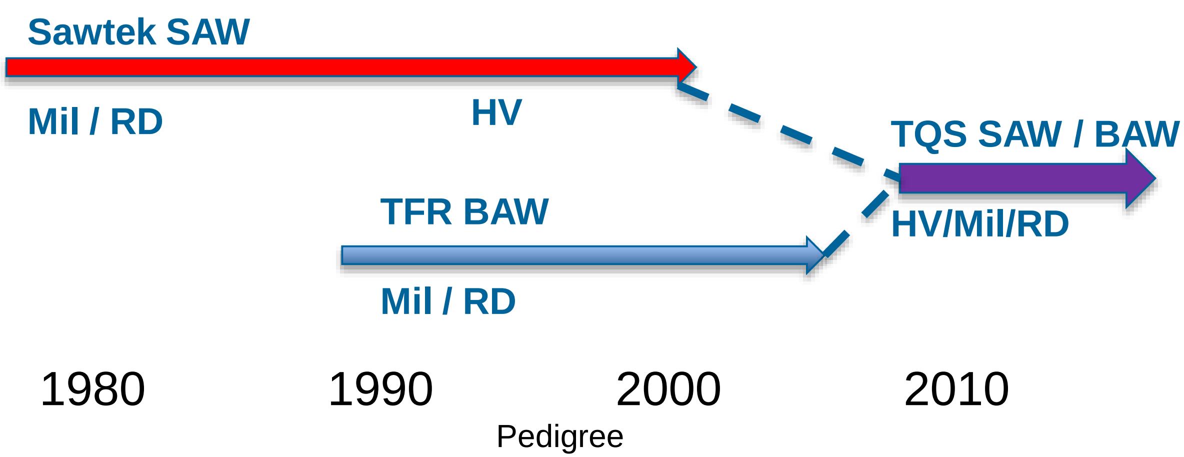
TriQuint Semiconductor
Exploring thin-film BAW Sensors

PWST 2013

Introduction

Motivation of this presentation is to open and explore the possibility of using thin-film Bulk Acoustic Wave (BAW) resonators in applications requiring high sensitivity and small form factor…today.





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TriQuint and Sensors

- **What are we doing?**
  - **Shipping prototype and pre-production sensor die to several customers**
  - **Developing proprietary uniform shear-mode (tilted-grain) deposition of AlN**

- **Why are we doing it?**
  - **Agile low-volume production facility – Design through Ship – Bend, OR**
  - **To explore material properties and sensitivity limits of our technology**

- **How are we doing it?**
  - **100 years combined BAW expertise**
  - **Collaborating with sensor customers on contact finishes and coatings**
  - **Ultimate low-cost capability exists on our high-volume BAW line**

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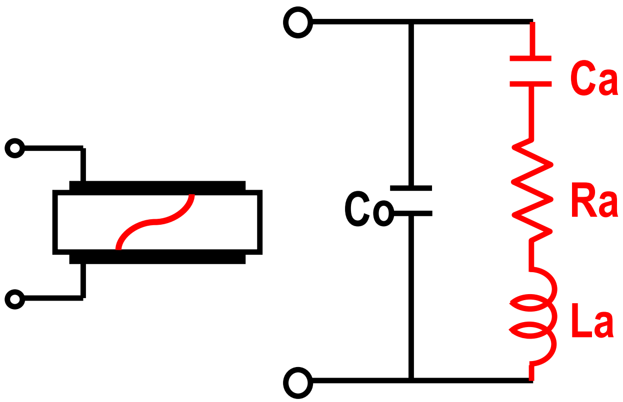
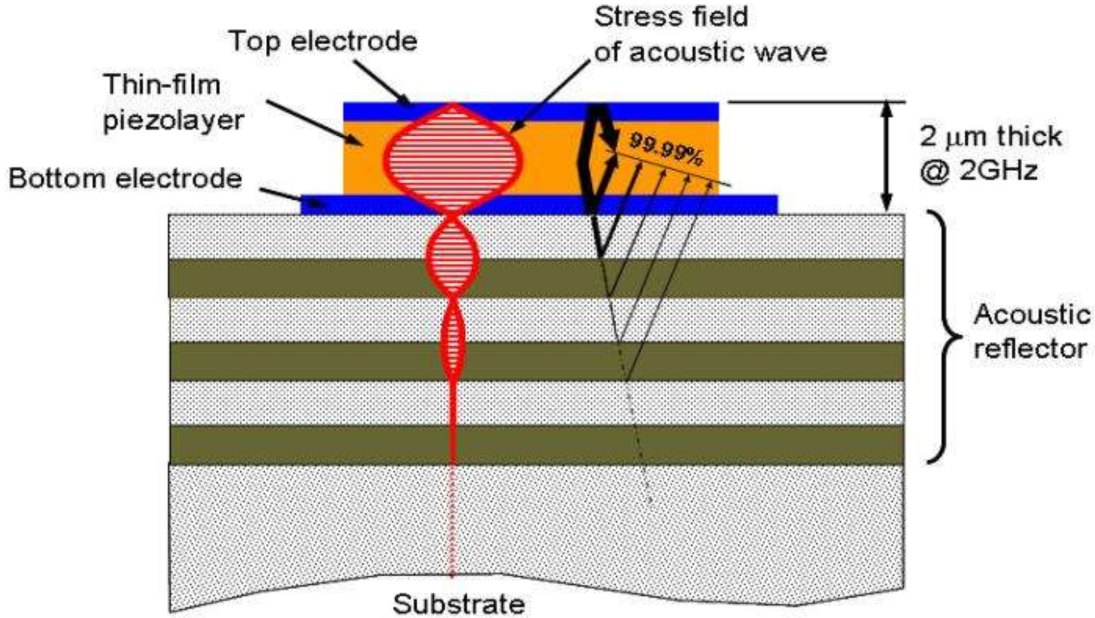
SMR BAW Resonator





- SMR is Solidly Mounted Resonator
- A piezoelectric material with conductive electrodes on top and bottom is used to convert electrical energy to vertically oriented standing wave acoustic energy (mechanical waves) and back
- Electrodes should vibrate in the z-axis in opposite directions
- The thickness of this stack is 1/2λ
- An acoustic mirror is provided to isolate the bottom electrode from the silicon substrate
- Resonant frequency is inversely proportional to thickness

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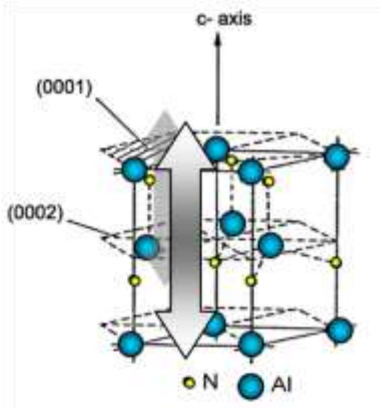
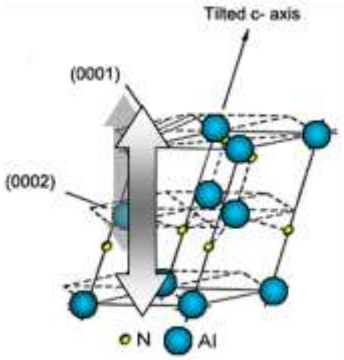
Piezolayer Structure

Longitudinal vs. Shear AlN

- **Longitudinal – c-axis is perpendicular to electrode surface**
  - Single mode resonance
  - Acoustic vibration is normal to surface of device
  - Acoustic energy is dissipated into liquid, causing dampening
  - Poor sensitivity and noise
- **Shear – c-axis is tilted relative to electrode surface**
  - Dual mode resonance
  - Acoustic vibration in plane of device - key attribute
  - Finite penetration of acoustic wave into liquid
  - Device has increased sensitivity to surface changes
  - Optimal shear mode response at c-axis tilt of ~50^o
  - >20^o of c-axis tilt is necessary for sensor functionality





C.-J. Chung et al.
Appl Phys A (2009) 94: 307–313

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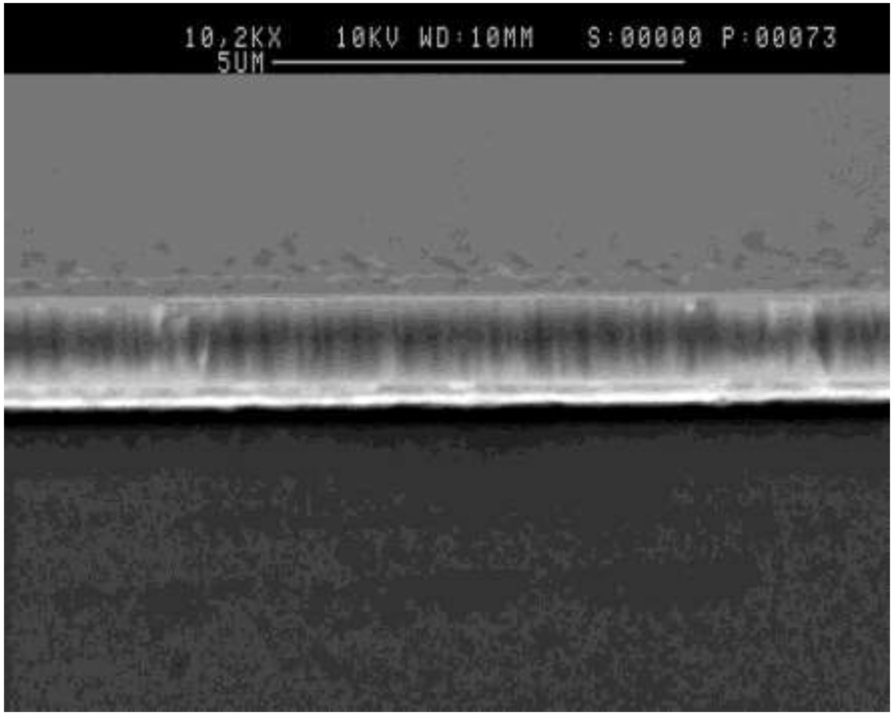
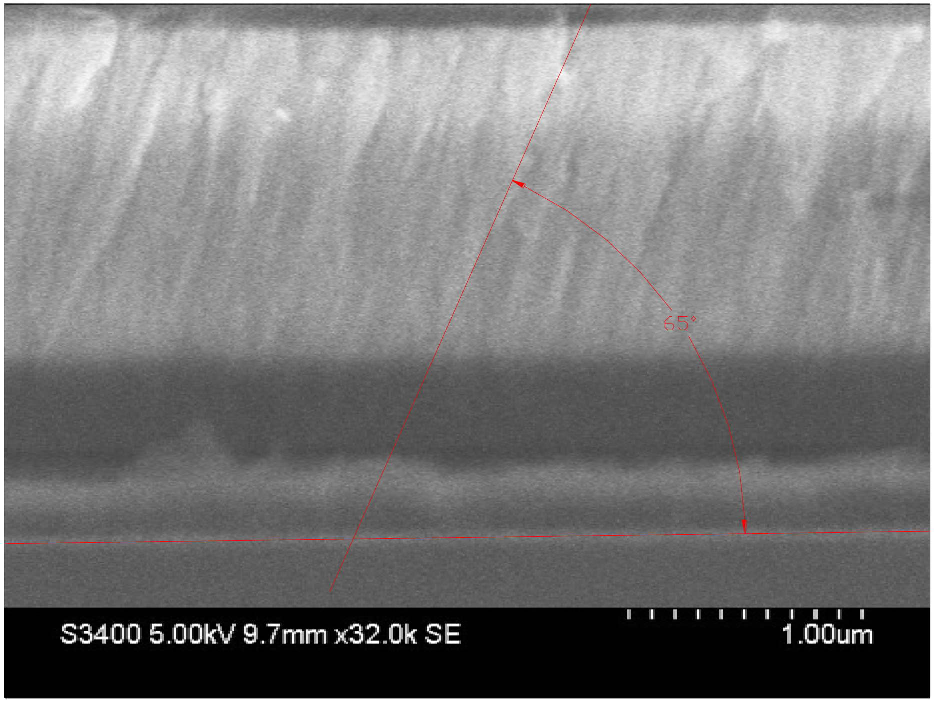
Sensor Structure



Longitudinal AlN



Shear AlN

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Sensitivity

- Sauerbrey Equation
  - Commonly used formula for mass to frequency conversion of acoustic resonator
  - Δf< 0.02, rigid mass, evenly distributed
  - Equation breaks down with liquid mass due to the interfacial liquid properties (density, viscosity, dielectric constant, etc.)

$$\Delta f = -\frac{2f_0^2}{A\sqrt{\rho_q \mu_q}}\Delta m.$$

Equation 1 – Sauerbrey's equation

f_0 – Resonant frequency (Hz)
Δf – Frequency change (Hz)
Δm – Mass change (g)
A – Piezoelectrically active crystal area (Area between electrodes, cm^2)
ρ_q – Density (g/cm^3)
μ_q – Shear modulus ($g/cm.s^2$)

	Quartz (QCM)	BAW @ 2 GHz	BAW @ 10 GHz
Res. Freq. (Hz)	30×10^6	2×10^9	1×10^{10}
Active Area (cm^2)	1.0	6.25×10^{-4}	2.5×10^{-5}
Density (g/cm^3)	2.7	3.3	3.3
Shear modulus ($g/cm*s^2$)	2.9×10^{11}	9×10^{11}	9×10^{11}
Sensitivity (Δf/Δm) **For a fixed amount of mass**	**2×10^9 Hz/g**	**7.4×10^{15}**	**4.6×10^{18}**
Sensitivity (Δf/Δm-A)	**2×10^9 Hz/g**	**4.6×10^{12}**	**1.1×10^{14}**

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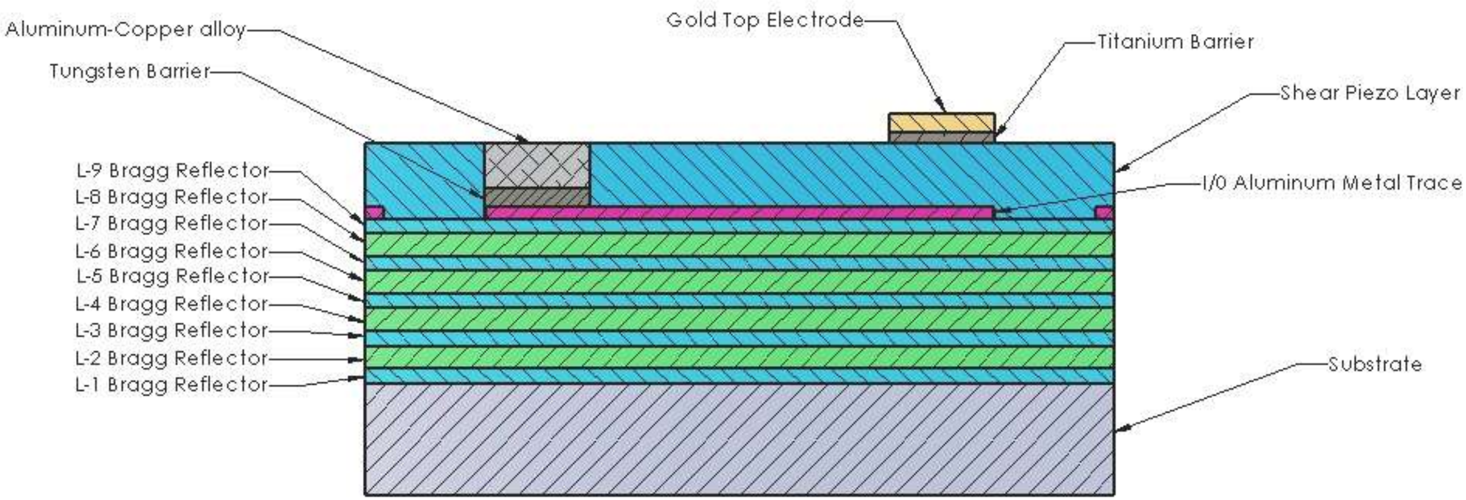
Sensor Structure

- **Resonator Structure**
  - **100mm Si substrate**
  - **SMR BAW resonator**
  - **Standard eight layer oxide reflector**
  - **Aluminum bottom electrode**
  - **Titanium/Gold or aluminum top electrode**
  - **Operating frequency of ~2GHz**



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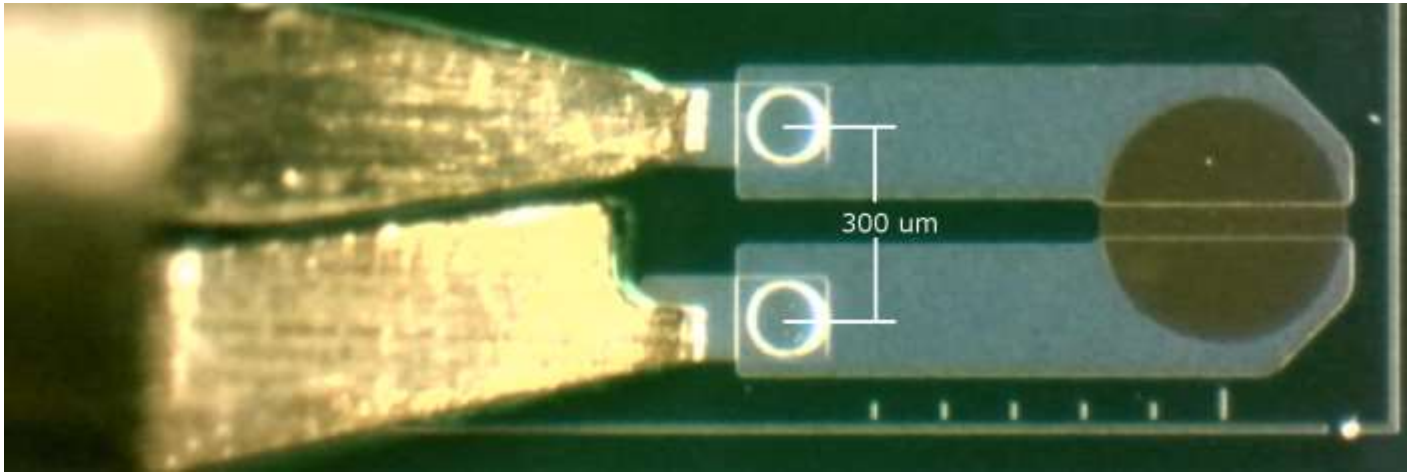
2 GHz Shear-Mode Resonator

- **Measured dry and with water droplet (full coverage)**
- **Some reduction in signal occurred due to water but resonator still has zero phase crossing**
- **Signal reduction with water mainly seen in anti-resonant Q and is likely a combination of electrical conductivity and mass-loading of water.**

  Measurement of device indicates ~ 1pF increase of parallel capacitance with water
- **There is also some loss in the longitudinal energy at the shear-mode frequency.**



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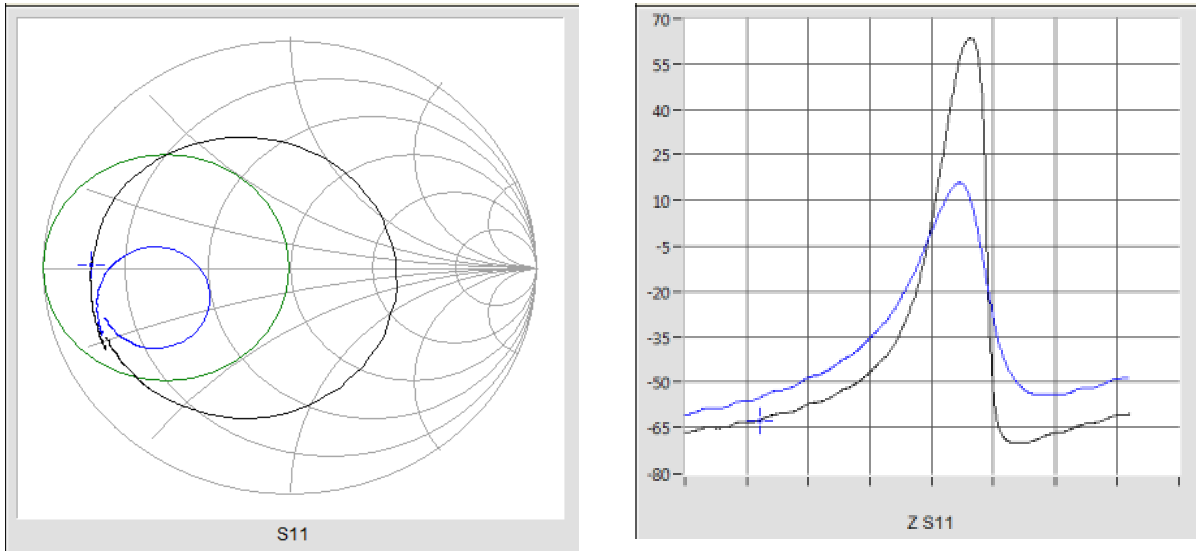
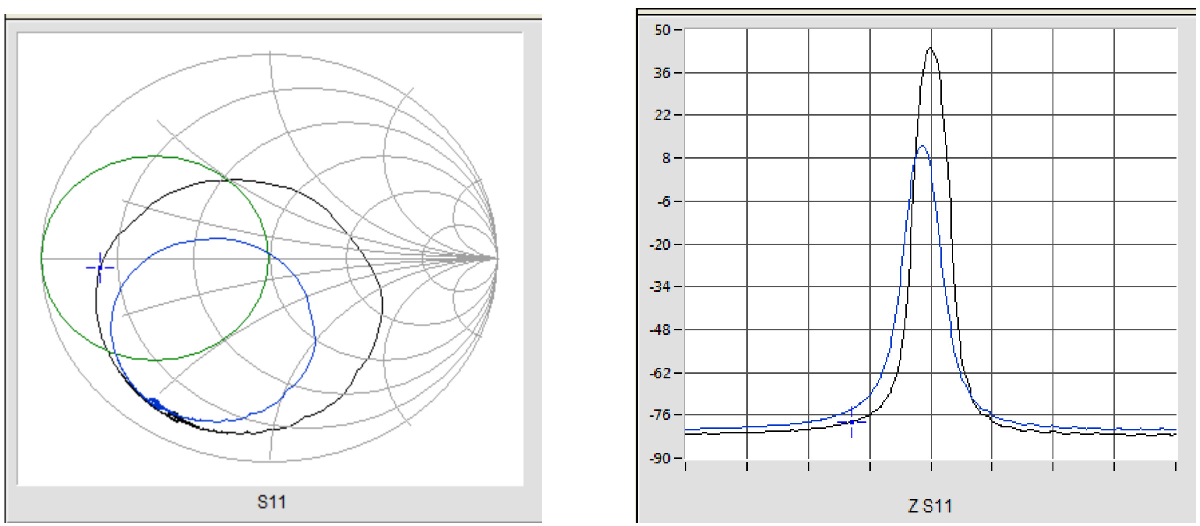
2 GHz Shear-Mode Resonator

Black – Dry
Blue - Wet



longitudinal-mode resonance



Shear-mode resonance

Outlook

Capability

Produced resonators up to 12 GHz, theoretically higher

Agile, custom fabrication and expertise

High-reliability MIL-STD heritage

High-volume factory and expertise – quick turn / low cost

Technology

Sauerbrey suggestion of sensitivity

Active area inversely proportional to frequency^2

Uniform shear-mode for aqueous sensing

Size – many sensors in small area

Possibilities?

Real-time POC

Corrosion/oxidation

Nano-molecular

“Lab on a tab”

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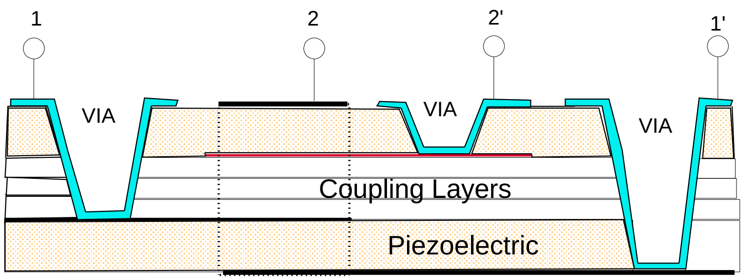
Opportunities for Exploration

- **Film quality at high Fo (longitudinal/shear)**
- **Full study to maximize Q/sensitivity**
  - **More complex structures**
  - **Novel materials / characterization**
- **Use with standard RFID technology**
- **Use for non-biological applications**
- ~~**Integration with actives??**~~



Coupled resonator filter

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Questions?

For more information:

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Backup

TriQuint -TFR

- 14,100 ft^2 Light Manufacturing Facility
  - 35% Manufacturing
  - 45% Engineering and Administration
  - 20% Available for Expansion
- Fully Contained Operation
  - Filter Design
  - Wafer Fabrication
  - Assembly
  - RF Test
  - Administrative functions are supported with corporate resources
    - Sales and Marketing, Human Resources, Accounting, Purchasing

- TFR Technologies History
  - Founded by Dr. Kenneth Lakin in 1989 at Iowa State University's Ames Laboratory
  - Moved to Central Oregon in 1991
  - Early years focused on development of technology
  - Producing production defense and aerospace filters since 1998
  - Purchased by TriQuint Semiconductor in 2005

- 100mm Wafer Fabrication Facility
- Design Group In House
- Thin Film Process Capabilities
  - 13 to 25 Films per Wafer
  - 5 to 11 Photo Layers
  - Film Thickness Range – 70Å to 8.0µm
  - Materials – SiO_2, Si_3N_4, AlN, Al, W, Cu, Ti, Au, Ni, Sn
- Hermitic Package Technology
- Wafer, Die, Packaged Device and Module Test Capability

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Typical SMR BAW Capabilities

Parameter	Typical Values MIN		Typical Values MAX	Comments
Frequency	500 MHz	⟷	12 GHz	Demonstrated 20 GHz theoretical
Fractional Bandwidth	0.7 %	⟷	25 %	Determines material & device structure used
Package Size	1.5x0.8 mm	⟷	5.1x7.6 mm	0603 to 2030
Insertion Loss	0.8 dB	⟷	5 dB	Determined by material & device structure used
Power Handling	-	⟷	1 W+	Theoretical with power metallization

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TriQuint -TFR Technology

- Discrete Filter Types
- All filter topologies use common processes and packaging

Filter Type	Top Attribute	Complexity	Comment
Ladder	• Excellent Selectivity	•Low	•Most mature technology •Accounts for half of current products shipped •Space qualified
Stacked Crystal (SCF)	•Low Insertion Loss	•Moderate	•Lowest volume product shipped
Coupled Resonator (CRF)	•Wide Bandwidth	•High	•Accounts for half of current products shipped
Single Section Coupled Resonator (SCRF)	•Tunability – Enables Modules •Ultra Wide Bandwidth	•Very High	•Module requires external components
Hybrid	•Selectivity and Bandwidth	•Very High	•Discrete or Module application

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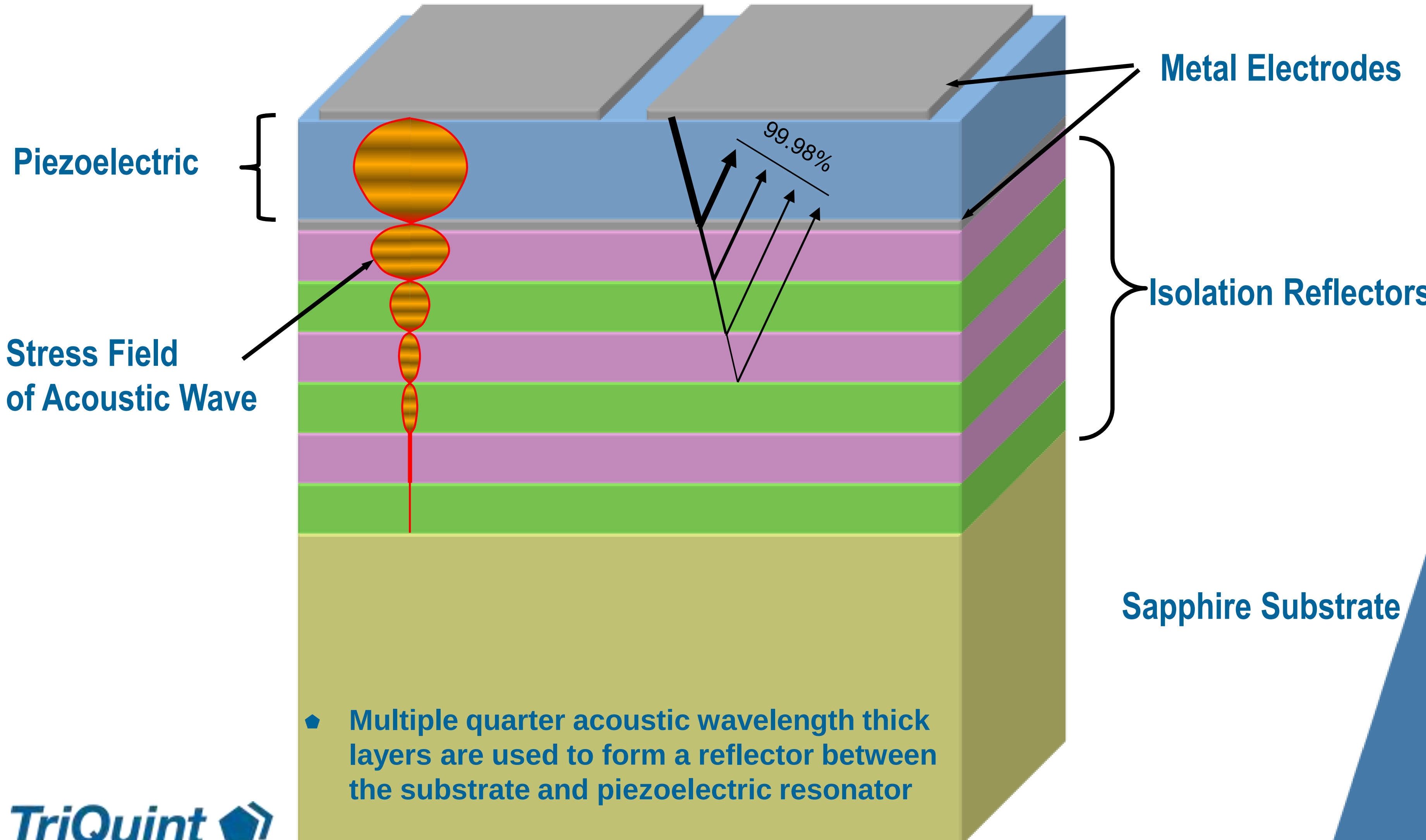
SMR BAW Filter Structure



- Multiple quarter acoustic wavelength thick layers are used to form a reflector between the substrate and piezoelectric resonator

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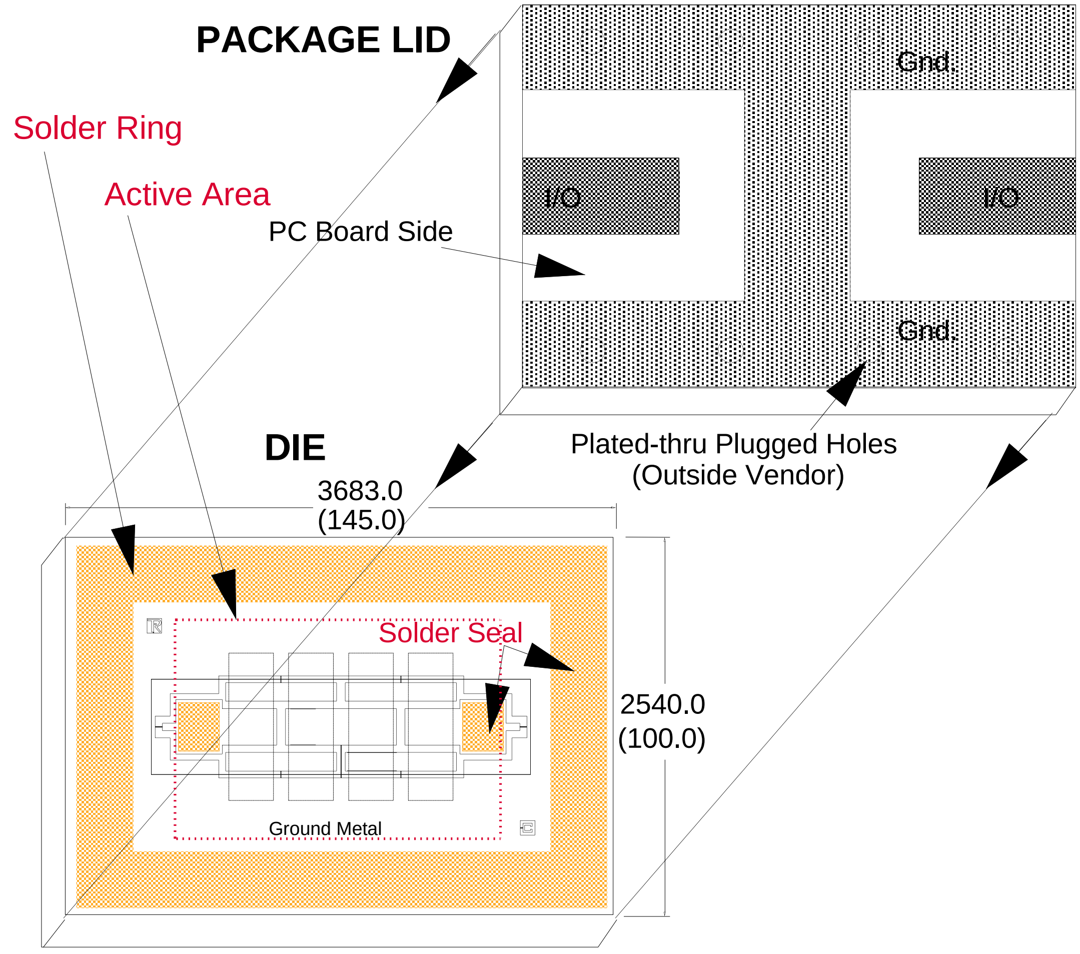
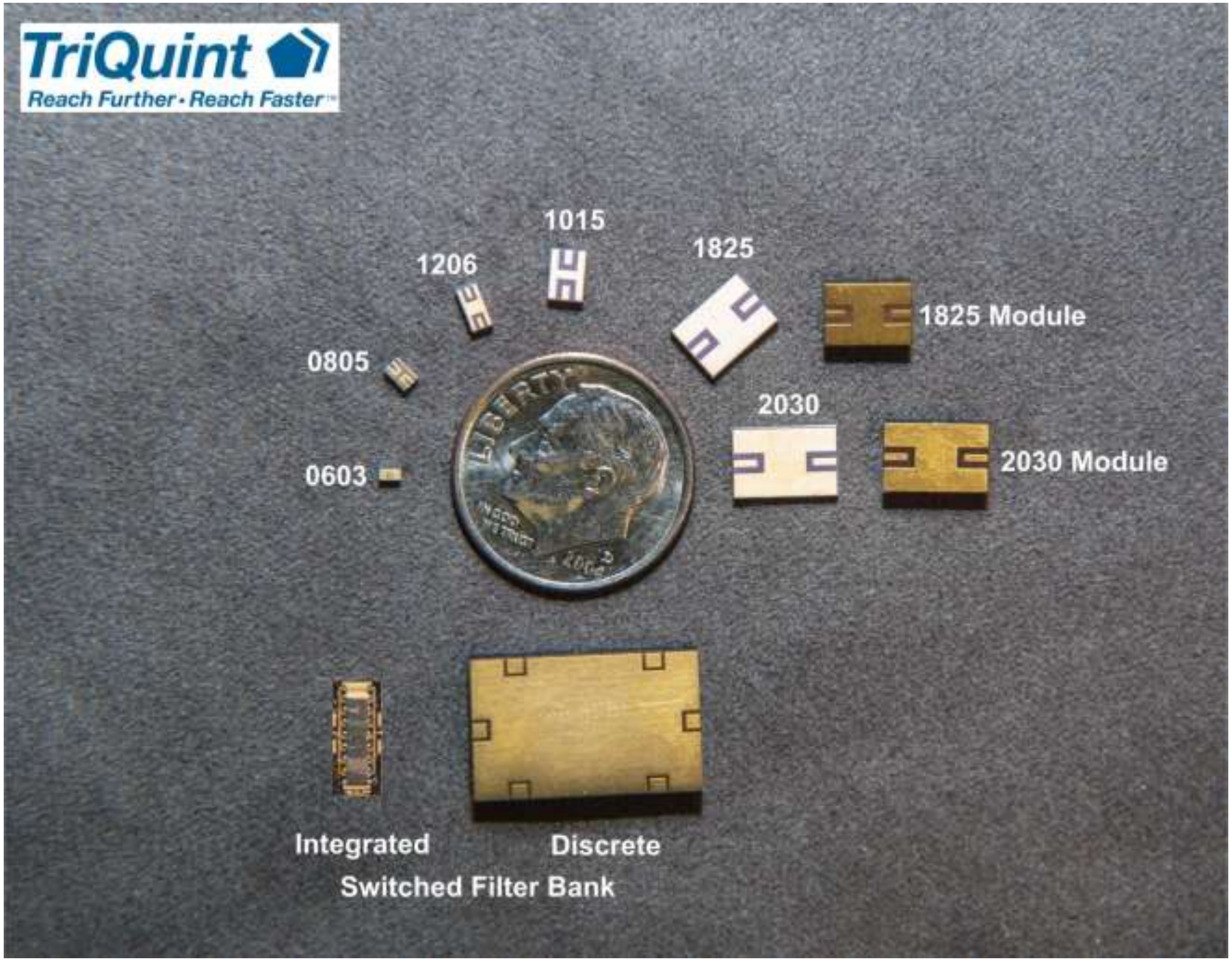
TriQuint-TFR Packaging

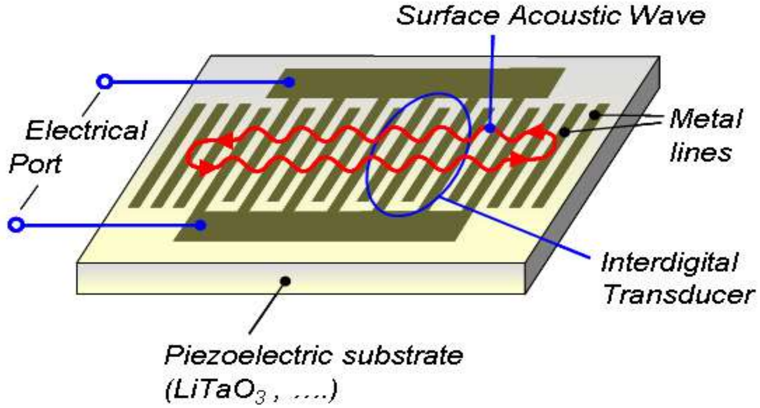
- Simple Chip Scale Package (CSP)
  - Covered under US Patent 6,114,635
  - Ceramic lid purchased from outside vendor
  - Matching solder ring and I/O pads on lid and die
  - Au and Sn added to solder ring side
  - Die and lid attached using reflow process
  - Au/Sn solder alloy allows 260C max reflow
- StandardSize Ranges From
  - 2030 (5.1mm x 7.6mm)
  - 0603 (1.5mm x 0.8mm)

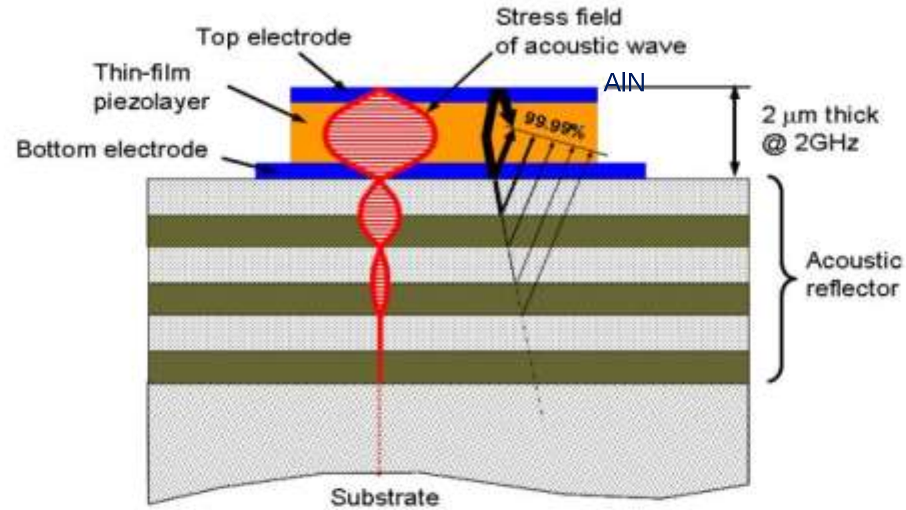


TriQuint-TFR Devices



SAW vs BAW



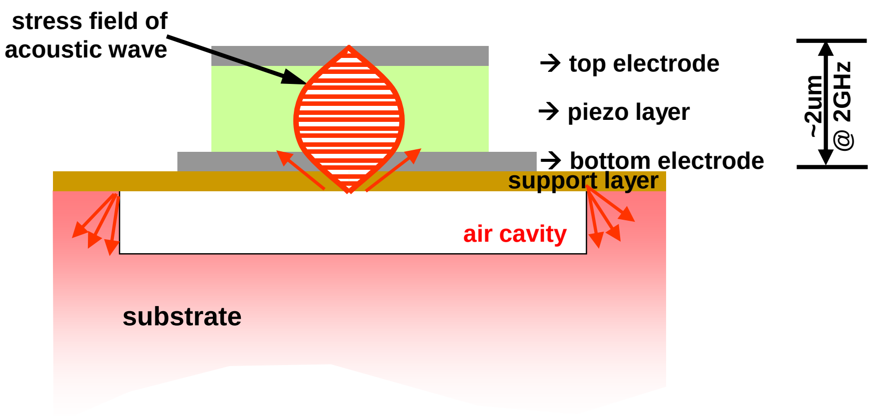


- SAW generally has better coupling (fractional BW capability) than BAW
- BAW has better tempco and Q (filter skirts) than SAW
- TC-BAW may be developed for very narrow band or VCO applications

Substrate	Coupling	Est Frac BW	Tempco	Drift 2GHz 110ºC	Q
Lithium Tantalate	8.0%	3.0%	-42ppm/ºC	-9.2MHz	800
Lithium Niobate	8.0%	3.0%	-25ppm/ºC	-5.5MHz	800
Aluminum Nitride	6.6%	2.5%	-20ppm/ºC	-4.4MHz	2200

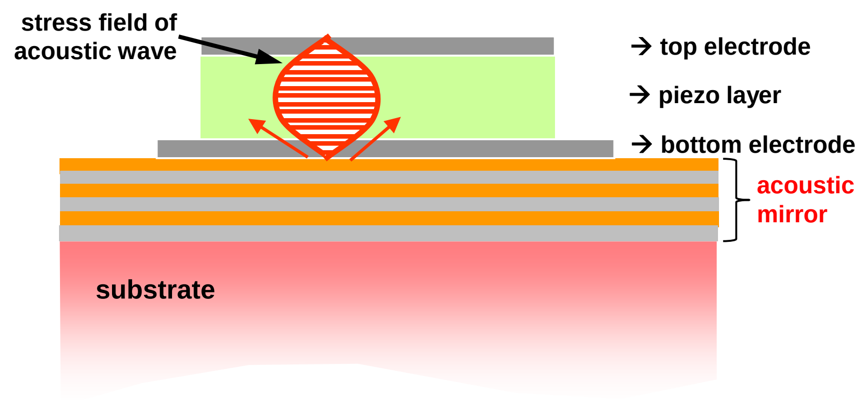
BAW Technology – FBAR vs. SMR

BAW: FBAR type
Film **B**ulk **A**coustic **R**esonator



- ⊕ High Q (steep filters)
- ⊕ Wide bandwidth
- ⊖ Power Handling (*air* is a poor heat conductor)
- ⊖ Larger intrinsic TCF (~26ppm/ºC)
- ⊖ Mechanical Robustness
- ⊖ Spurs as ripple in passband (apodization can reduce)
- ⊖ Advanced device topologies hard to implement (CRF)
- ⊖ Hard to manufacture (stress control)

BAW: SMR type
Solidly **M**ounted **R**esonator



- ⊕ High Q (steep filters)
- ⊕ Wide bandwidth
- ⊕ Better Power handling than FBAR
- ⊕ Lower intrinsic TCF (~20ppm/ºC)
- ⊕ Mechanically very robust
- ⊕ Effective spurious mode suppression
- ⊕ Advanced device topologies easy to implement (CRF)
- ⊖ More layers