AlN and AlScN RF Microsystems

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https://youtu.be/UCS4x1OlQ4Y

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MEMS in Consumer Products

Technology x market development

MEMS 1.0
Stand-alone

MEMS 1.2
Combos

MEMS 1.5
Combos in a single package

MEMS 2.0
Sensor Networks

MEMS 2.5
Smart sensors (edge AI)

MEMS 3.0
Sensing and Actuating

Robotic servants
Autonomous vehicles
IoT nodes
Smart homes
Voice HMI
AR/VR
Environmental hubs
Wearables' boom
Safety applications
Smartphone boom
Hearables/VPA boom
Automotive

1990 | 20 years | 2010 | 10 years | 2020 | 5 years | 2025 | 5 years? | 2030?

Acceleration of development

https://s3.i-micronews.com/uploads/2021/10/ILLUS_MEMS_INDUSTRY_Roadmap_Oct2021.jpg

Piezo MEMS in Consumer Products

Piezo MEMS time to market: 2018-2025

(Source: Status of the MEMS Industry 2019, Yole Développement, June 2019)

Start time of thin film technology availability for commercial products

MEMS gyroscope

BAW Filters

Inkjet printheads

Microphones

Microspeakers

PMUT – Gesture recognition

Autofocus

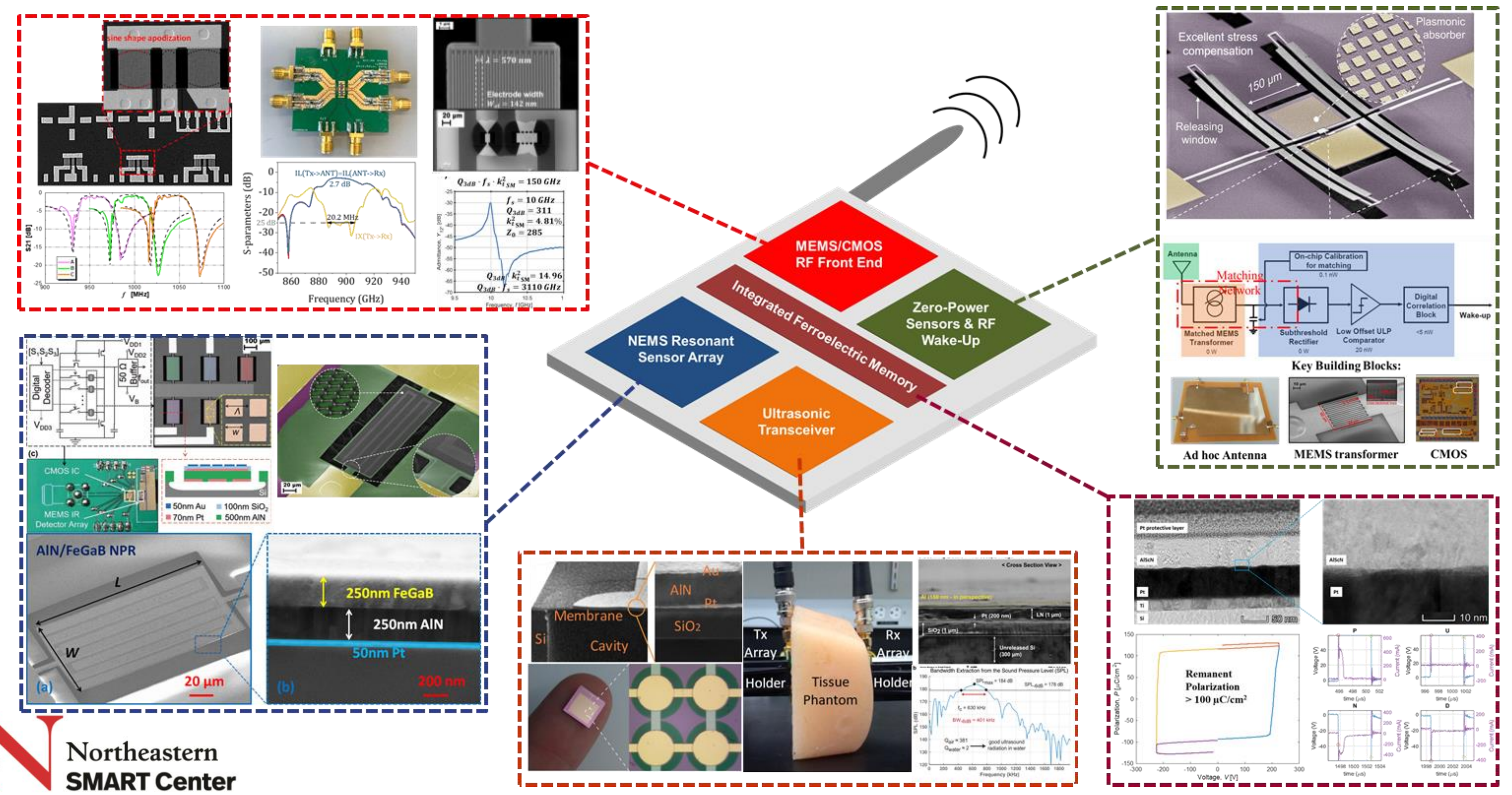
PMUT for fingerprint

PMUT for Ultrasound probe

Micropumps

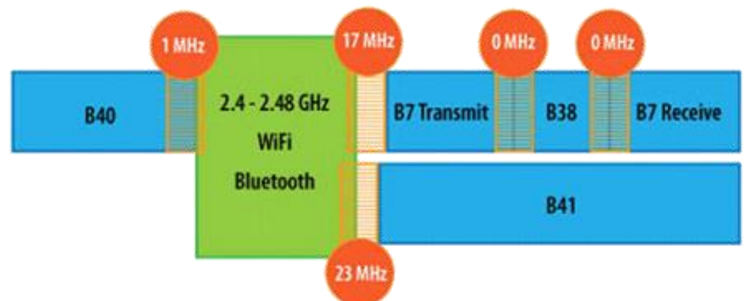
2005 2010 2015 2020 2025

Multi-Functional and Near-Zero Power Piezo Microsystems



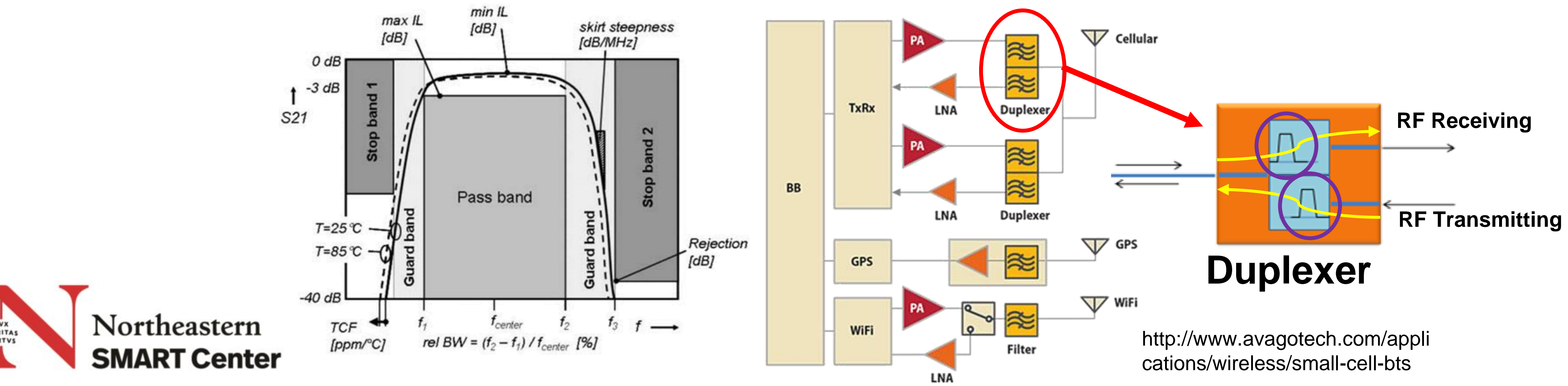
Radio Frequency Filters - Needs

- 4G/LTE frequency bands are often co-located next to other frequency bands with little to no guard band separating adjacent bands and have challenging TX/RX frequency separation



http://www.avagotech.com/products/wireless/fbar/

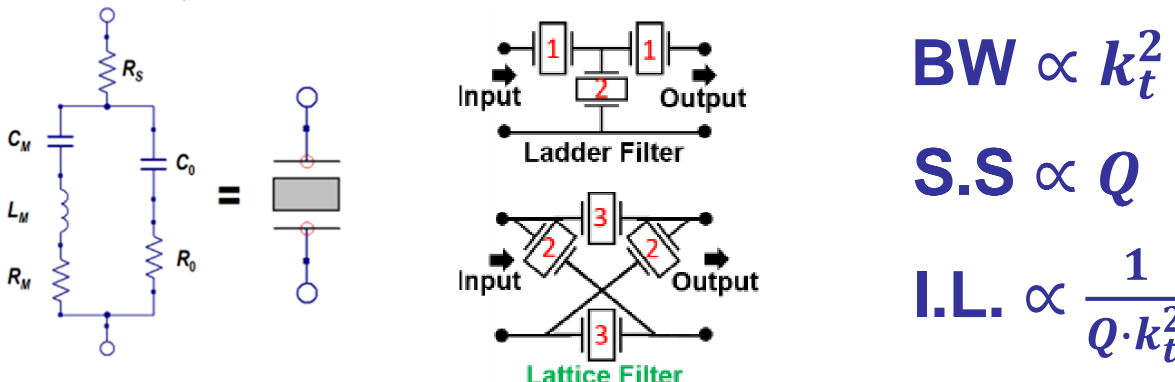
- Miniaturized RF filters with **low-loss**, **large skirt steepness** and **out of band rejection** are required to satisfy the 4G/LTE stringent **multi-band operation** requirements:



http://www.avagotech.com/applications/wireless/small-cell-bts

Microacoustic RF Filters

- Micro acoustic resonators guarantee high Q in a reduced form factor not achievable with LC networks
- N^{th}-order filters are formed by N micro-acoustic resonators electrically (or mechanically) coupled

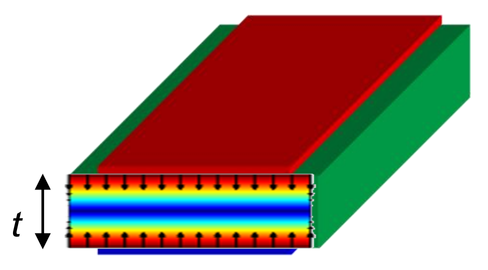


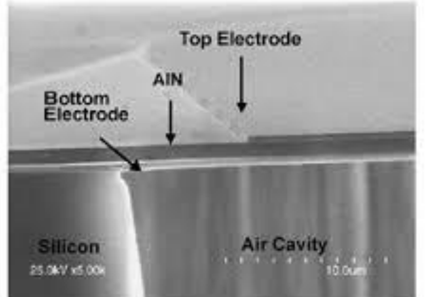
$$BW \propto k_t^2$$

$$S.S \propto Q$$

$$I.L. \propto \frac{1}{Q \cdot k_t^2}$$

- Aluminum Nitride FBAR (Film Bulk Acoustic Resonator) has gone mainstream thanks to superior performance with steeper rejection curves compared to surface acoustic wave (SAW) filters





Ruby et al.

SAW Filter
FBAR Filter
Lower Insertion Loss for Longer Battery Life & Fewer Dropped Calls
Steeper Filtering for Better Coexistence with Adjacent Bands
Better Out-of-Band Rejection Enables Multi-Band Capability

http://www.avagotech.com/products/wireless/fbar/

AlN Microacoustic RF Filters

Technology	Mode Shape	f_0	k_t^2	Q	Frequency Tuning
FBAR	t	$\propto \frac{1}{T}$	$\propto {e_{33}}^2 \approx 5\sim7\%$	$1000 \sim 5000$	*Non lithographic*
CMR	W	$\propto \frac{1}{W}$	$\propto {e_{31}}^2 \approx 1\sim2\%$	$1000 \sim 5000$	*Lithographic (full range)*
CLMR*	W, t	$f_r \propto \frac{1}{T}, \frac{1}{W}$	$\propto \frac{2}{\pi}\left({e_{31}}^2 + {e_{33}}^2\right) \approx \approx 5\sim7\%$	$1000 \sim 5000$	*Lithographic* $\left(40\%, k_t^2 \geq 5\%\right)$

* *C. Cassella, et al., "Aluminum Nitride Cross-Sectional Lamé Mode Resonators," J. Microelectromechanical Syst., pp. 1–11, 2016.*

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Cross-Sectional Lamé Mode Resonators

$$\begin{bmatrix}\mu_x \\ \mu_z\end{bmatrix} = \begin{bmatrix}A(x)B(z) \\ C(x)D(z)\end{bmatrix} = \begin{bmatrix}\cos(\beta_x x)\, sin(\beta_z z) \\ -\sin(\beta_x x)\, cos(\beta_z z)\end{bmatrix}$$

2-D Displacement vector

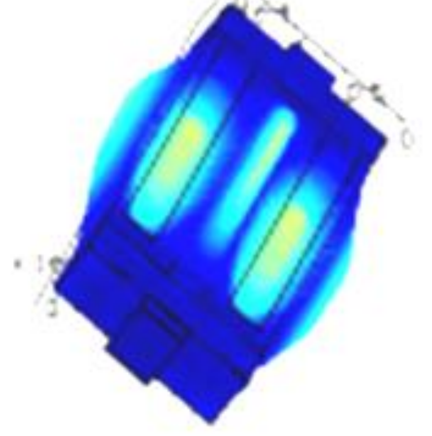
$$f_r = \frac{1}{\lambda_x}\sqrt{\frac{C_{11}C_{33} - C_{55}{}^2 + (C_{13} + C_{55})\sqrt{(C_{11} - C_{55})(C_{33} - C_{55})}}{(C_{33} - C_{55})\,\rho}}$$

max
min
T_{AlN}
Total Displacement
λ_x=2W
Analytical
FEM
f_r [GHz]
λ_x [µm]
12 10 8 6 4 2 0
0 2 4 6 8 10

Lamé mode **exact** solution:

$$\frac{W}{T_{AlN}} = \sqrt{\frac{(C_{11} - C_{55})}{(C_{33} - C_{55})}} \sim 1$$

$$\boldsymbol{\mu_x^{peak}} = \boldsymbol{\mu_z^{peak}}$$



Lamé mode **degenerate** solutions:

$$\frac{W}{T_{AlN}} \neq \sqrt{\frac{(C_{11}C_{55})}{(C_{33} - C_{55})}}$$

$C_{x,y}$=Components of the AlN stiffness matrix

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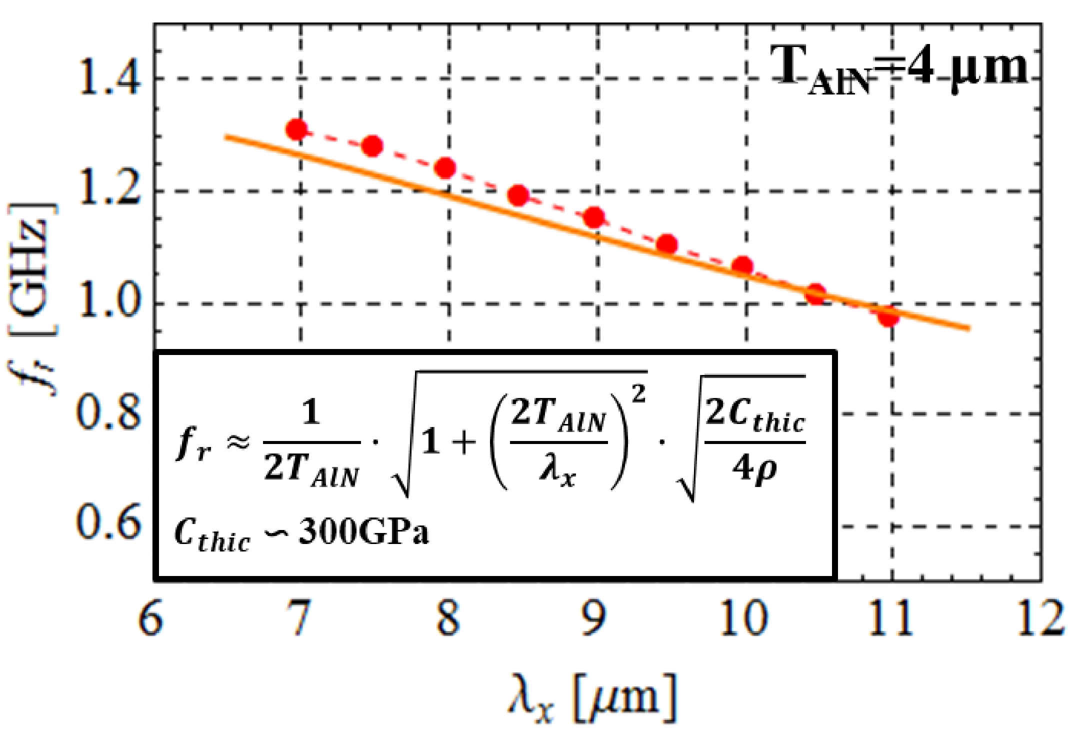
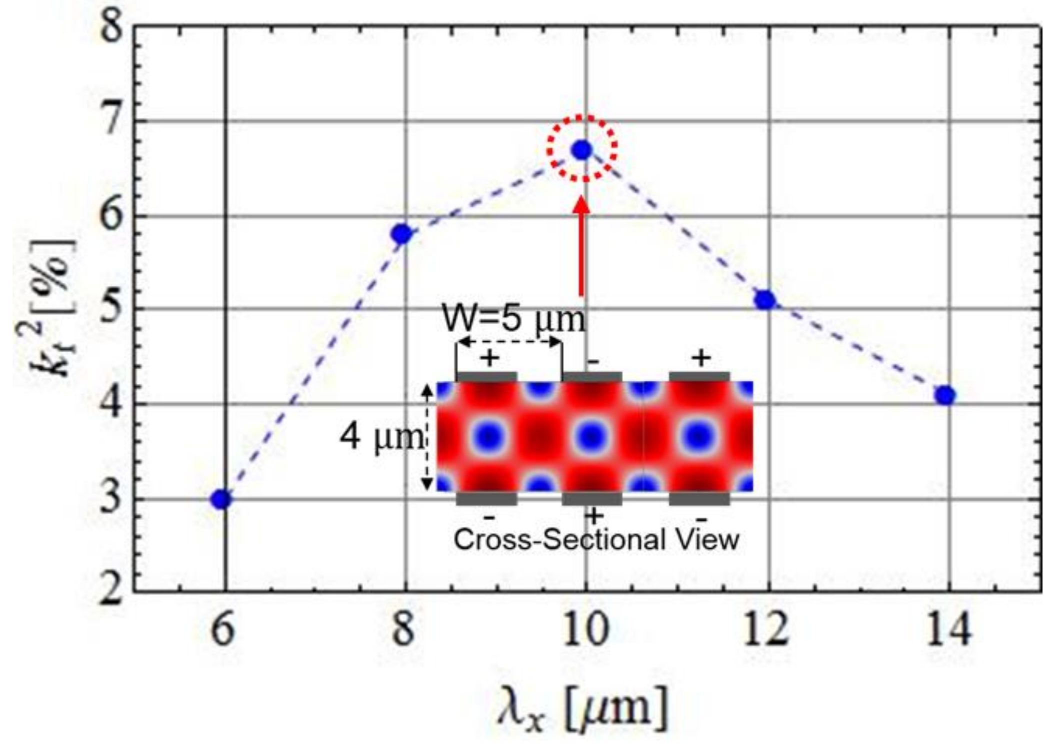
Cross-Sectional Lamé Mode Resonators

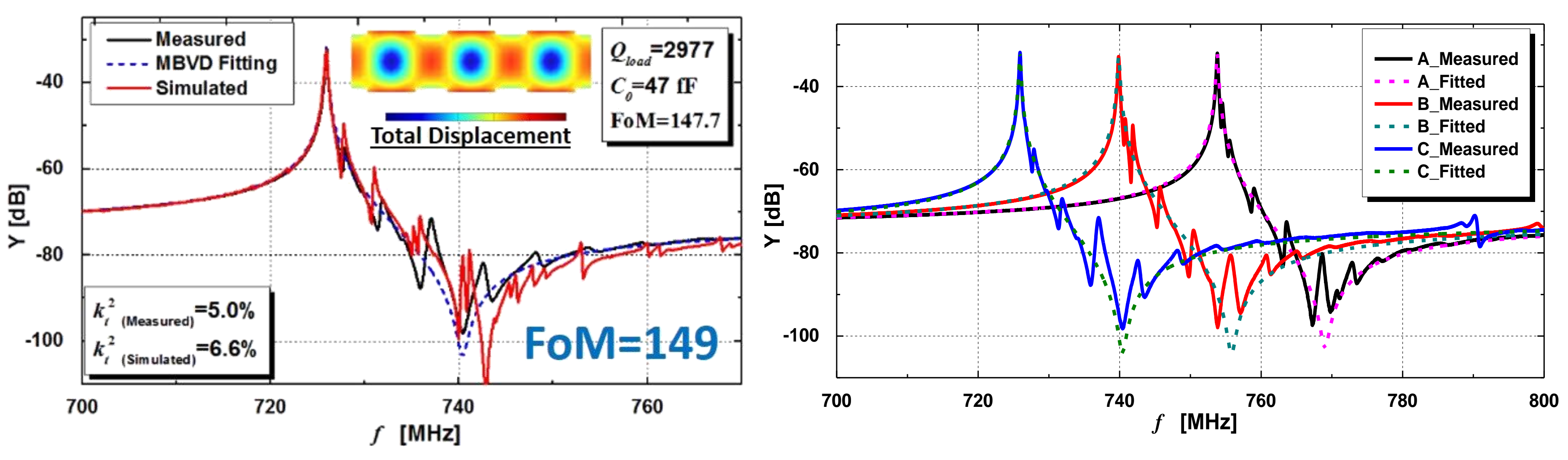
Degenerate CLM - $u_x^{peak} \neq u_z^{peak}$ but k_t^2 can be high-enough in a broad range of λ_x/T_{AlN}

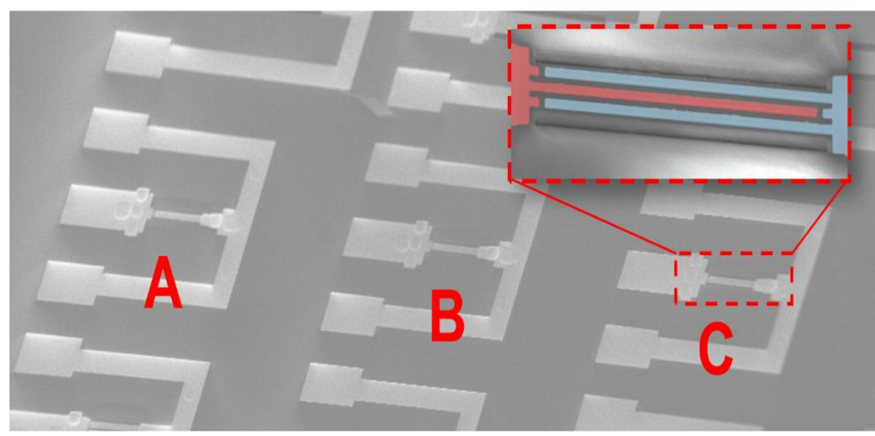




>40% lithographic tuning with $k_t^2 \geq 5\%$

AlN Cross-Sectional Lamé Mode Resonators – Record FoM

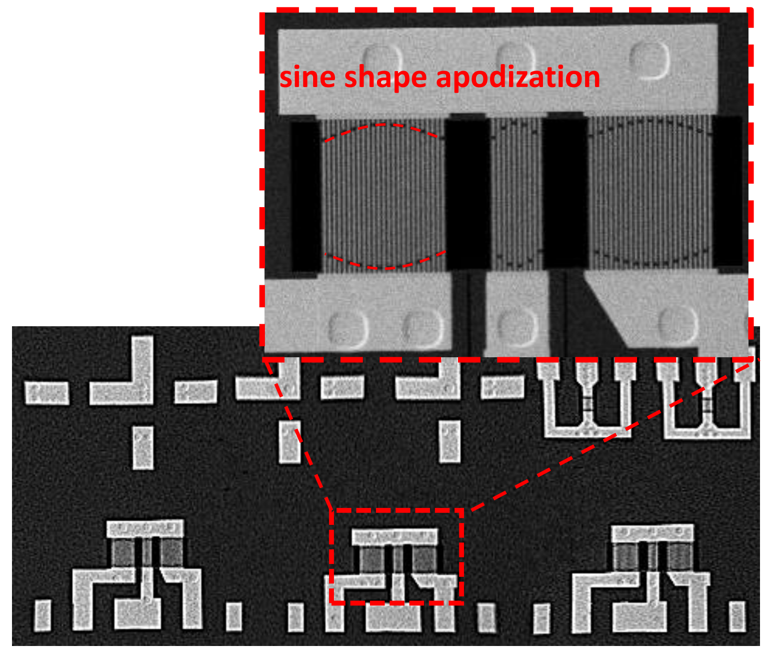


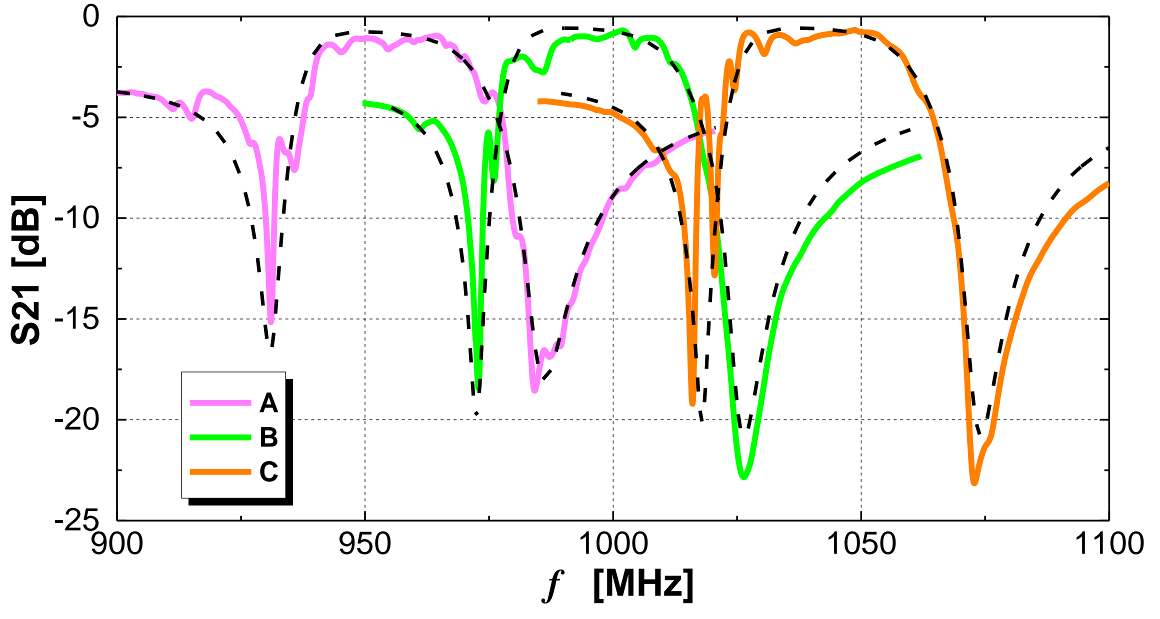


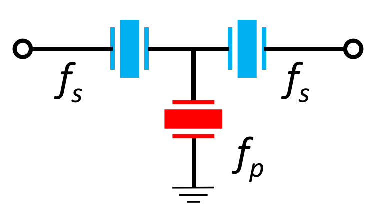
Device	Pitch [µm]	Q_{load}	k_t^2	f_r [MHz]	FoM
A	5.0	2820	5.0%	753.8	141.0
B	5.2	2493	5.4%	739.9	134.6
C	5.4	2977	5.0%	725.9	147.7

AlN Cross-Sectional Lamé Mode Filters

High fractional bandwidth (***BW>3.9%***) and unprecedented levels of loss (***IL<1dB***) and ***spurious suppression*** enabled by the combined use of thicker platinum electrodes and **apodization techniques**



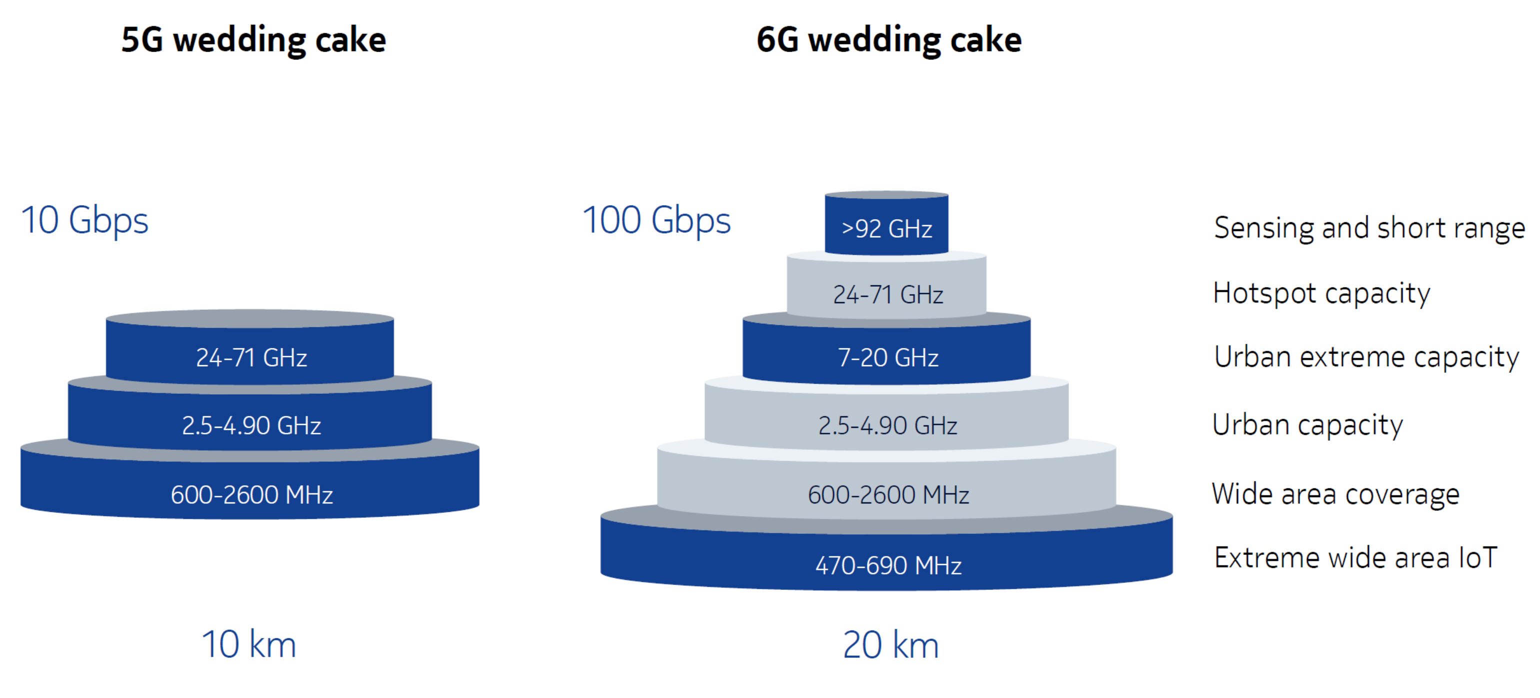




Filter	Resonator	Pitch [µm]	Comsol Simulation		Fitting		Measurement		
			Static Capacitance [fF]	k_t^2	k_t^2	FBW	IL [dB]	FBW	Termination
A	Series	4.9	358	7.6%	6.5%	3.9%	0.9	4.0%	700 Ω
	Parallel	5.1	146	7.6%					
B	Series	4.6	346	7.5%	6.5%	3.7%	0.7	3.9%	
	Parallel	4.8	141	7.4%					
C	Series	4.3	334	7.1%	6.5%	3.8%	0.7	4.0%	
	Parallel	4.5	136	7.4%					

G. Chen, et al., *IEEE MEMS 2018*, Jan 21-25, 2018

New Paradigms and Opportunities for the 6G Spectrum

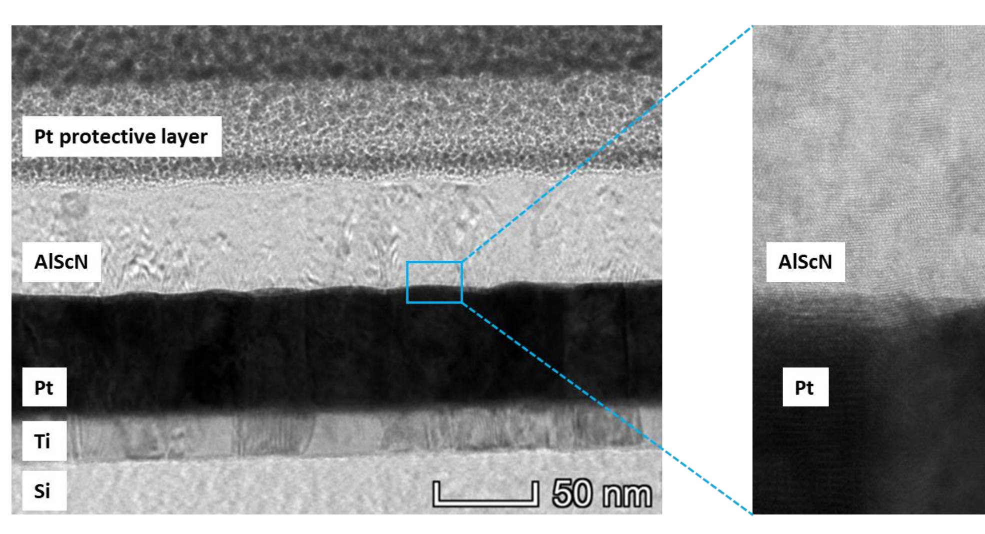


H. Holma, et al., “Extreme massive MIMO for macro cell capacity boost in 5G-Advanced and 6G.” Nokia Bell Labs

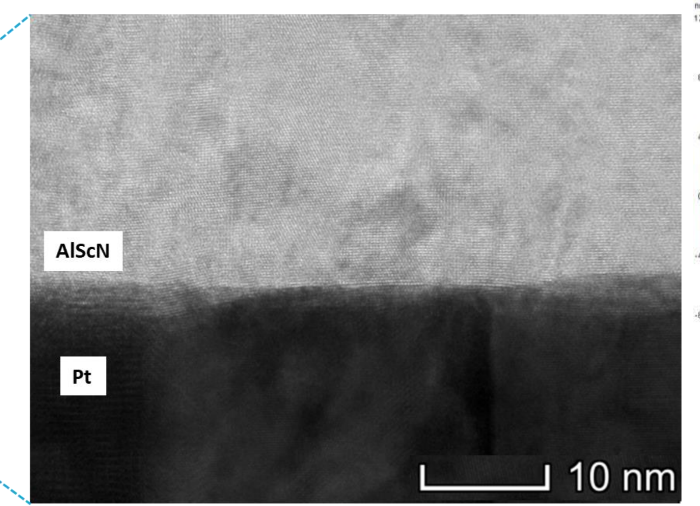
Resonator Metric	Low spectrum	Mid Spectrum
Frequency	470-690 MHz	7-20 GHz
k_t^2 (~BW)	>10%	>4%
Q	>500	>250

Breakthroughs in resonator material and design highly needed

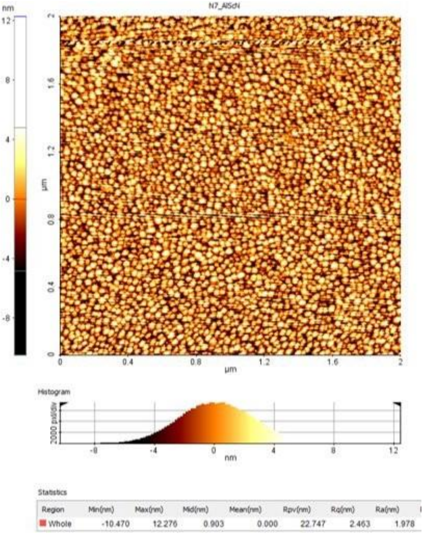
Sc-Doped AlN Material Platform for the 6G Spectrum

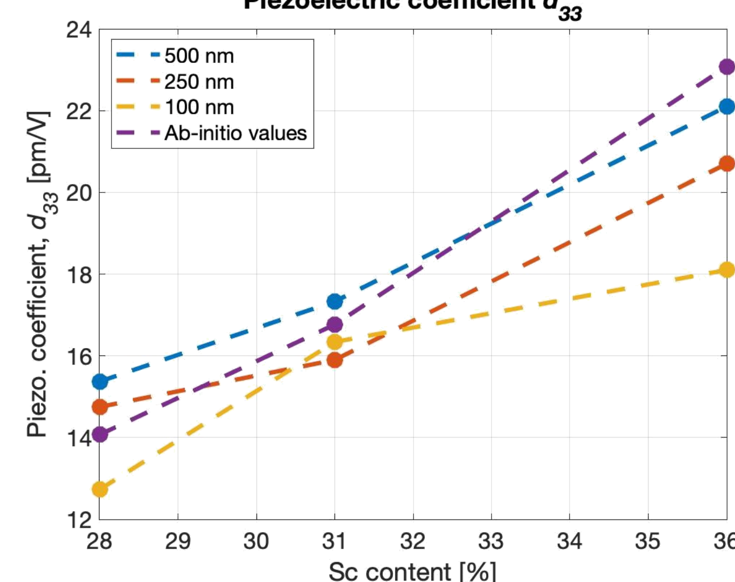


TEM image of $Al_{69}Sc_{31}N$ film deposited on top of Si+Ti+Pt layer stack



TEM image of $Al_{69}Sc_{31}N$ –Pt interface showing absence of a "dead layer"

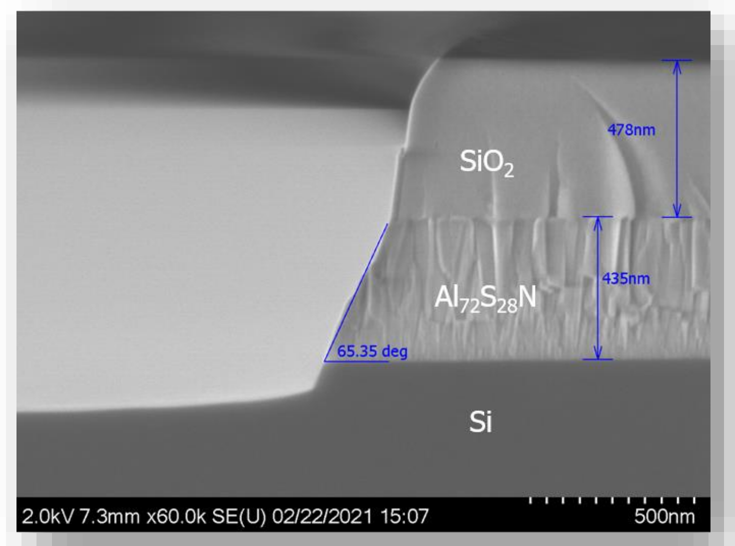




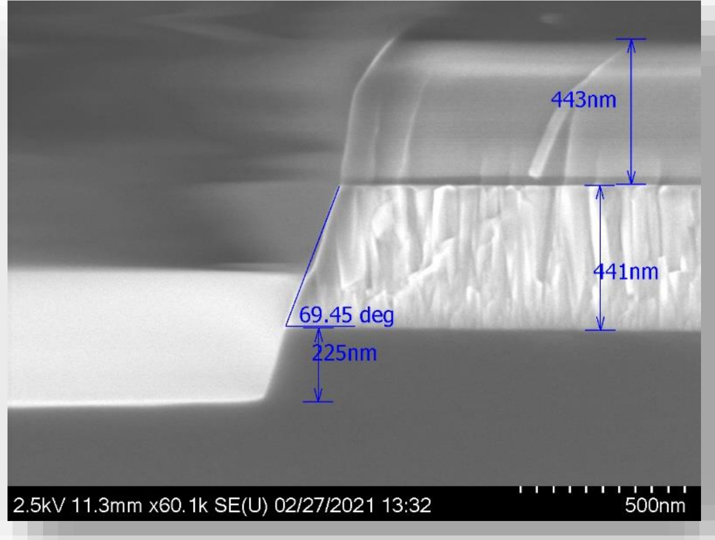
Property	Metric	Best Measurements	Range of Measured Data
Material quality	XRD full-width-half-maximum with >90% single phase	1.43°	1.43° - 2.6°
	Surface Roughness	0.9 nm	0.9 - 2.07 nm
	Film Thickness Range	101 – 700 nm	101- 700 nm
	Film stress range	25 MPa	-309 – 414 MPa
Composition	Doping value achieved	20% - 37%	20% - 37%
	Through-thickness composition variation	0.5%	0.5% - 2.2%
	Lateral film composition deviation per 100 mm	0.78%	0.78% - 3.55%
Electrical Properties	Dielectric constant	14	14 – 22.3
	Piezoelectric constant ($e_{31,f}$)	-2.2 C/m²	-1.4 - -2.2 C/m²
	Remnant polarization	171 μC/cm²	90 -171 μC/cm²
	Coercive field	3.38 MV/cm	3.38 - 5.43 MV/cm
	Polarization switching speed	0.8 μs	0.8 – 6 μs
	Tan δ values	0.016 @ 5kHz	0.016 - 0.049

Dry etch of AlScN

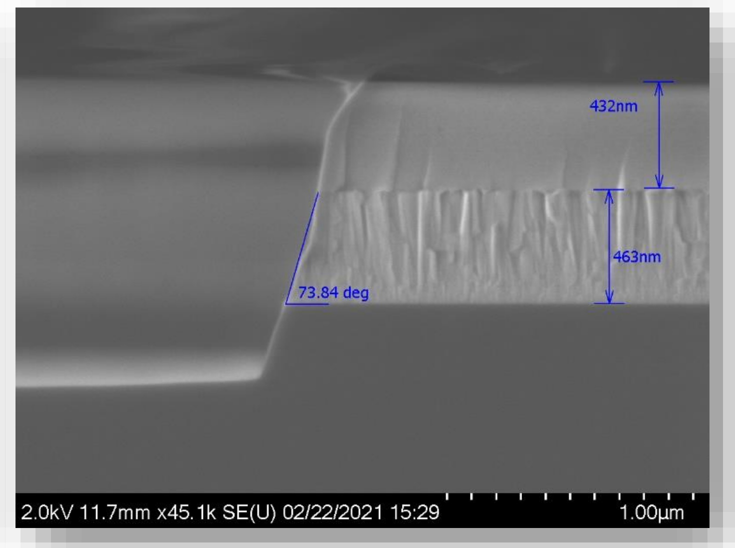
Bias Power= 200 W: ∠ ≈65 deg.



Bias Power= 300 W: ∠ ≈69 deg.



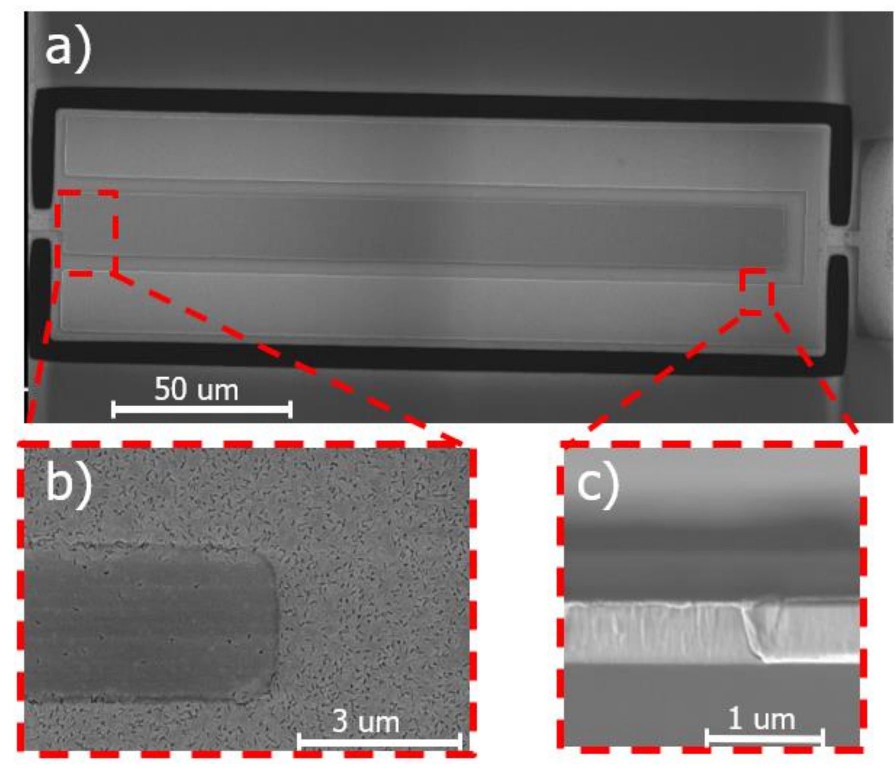
Bias Power= 400 W: ∠ ≈74 deg.

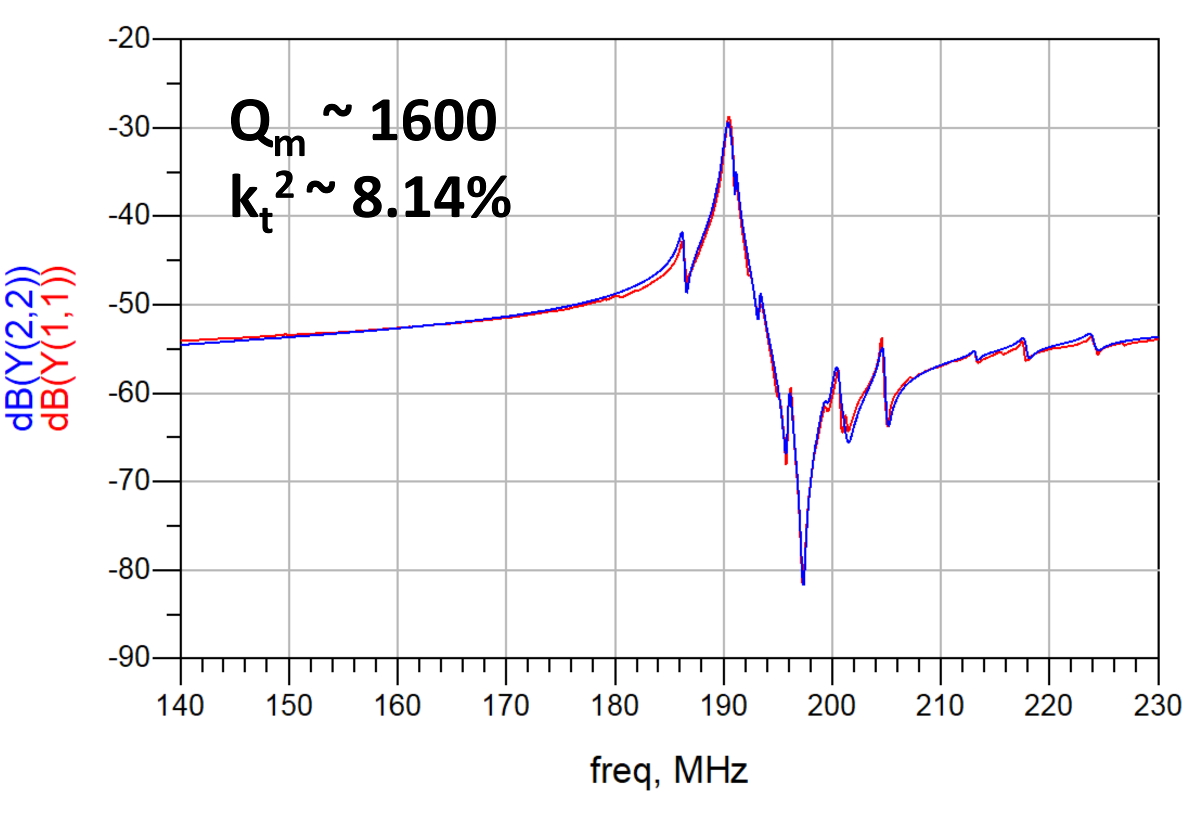


Parameter	**Value**
ICP Power	700 W
RF Bias Power	200-400W
Cl_2 Gas flow	10 sccm
BCl_2 Gas flow	6 sccm
Ar Gas flow	28 sccm
Chamber Pressure	10 mT

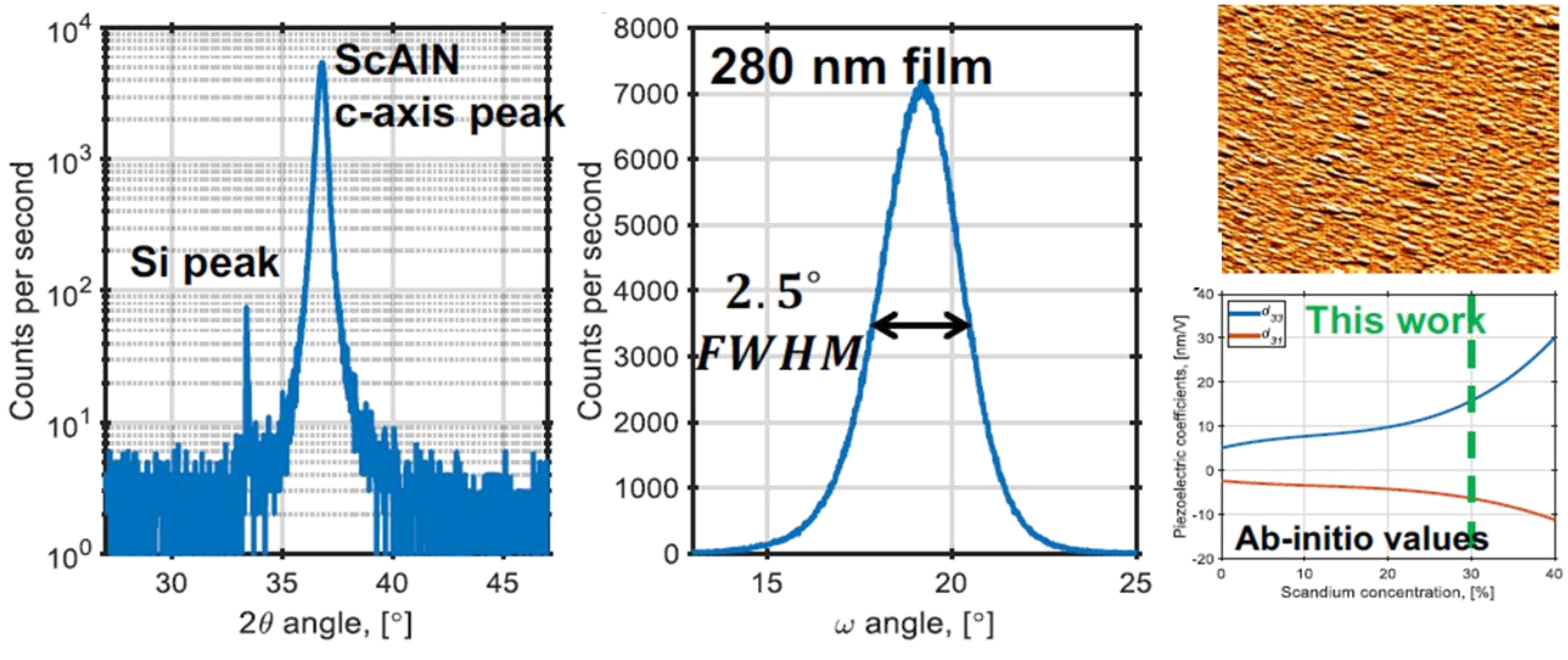
- Low Temperature SiO_2 is used as a hard mask and can be removed via wet etch in BOE or dry etch in $Ar/CF_4/CHF_3/H_2$ gas mixture.
- Etch rates: $Al_{72}Sc_{28}N$ = 140 nm/min,
  SiO_2 =120 nm/min
- Sidewall angle ≈ 74 deg.

28% Sc-doped AlN Contour Mode Resonators for Low 6G Spectrum

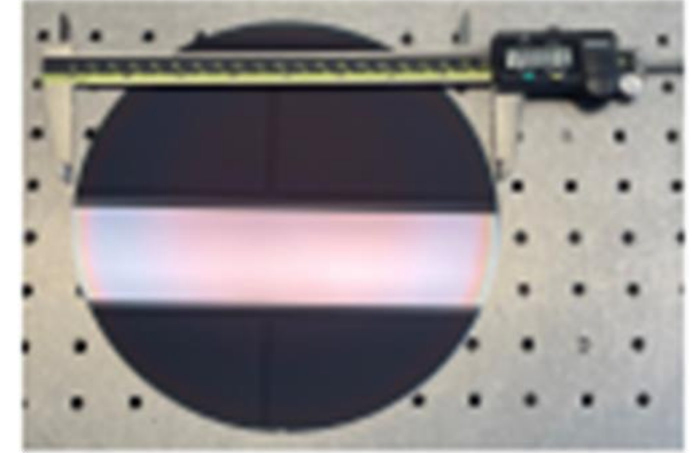




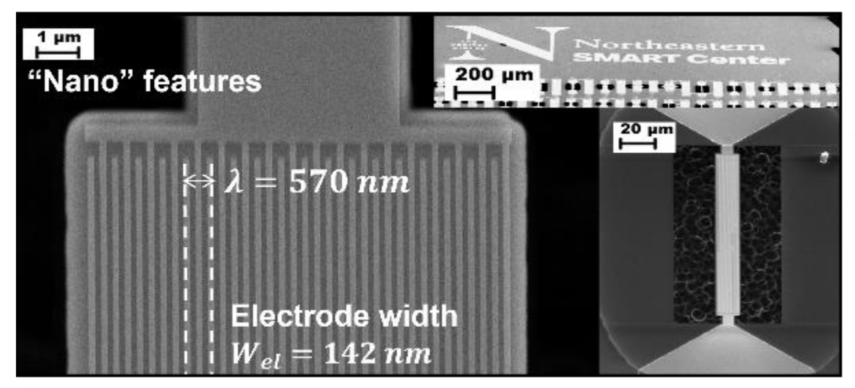
Films from 300 mm $AlSc_{30}N$ alloy sputtering target

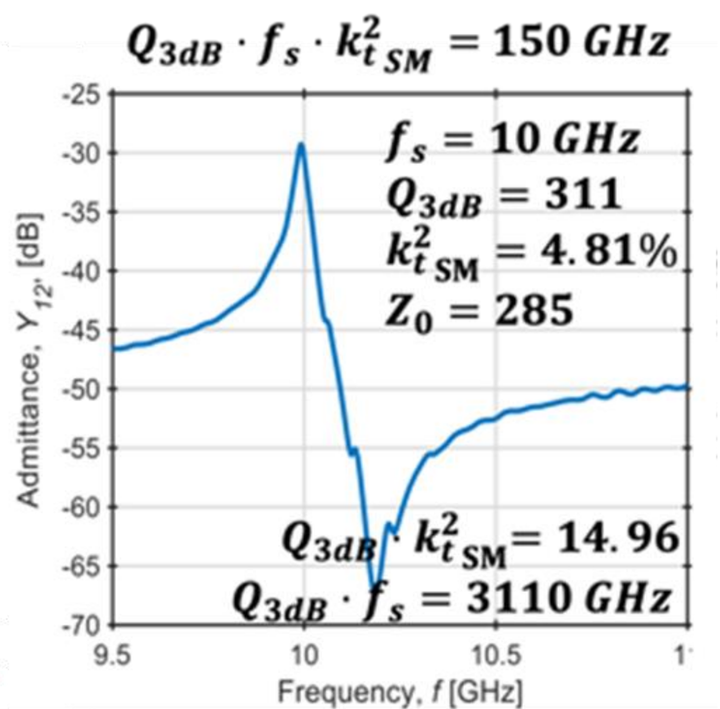


Parameter	Value
Power	5 kW
RF Bias Power	10 W
N_2 Gas flow	30 sccm
Ar_2 Gas flow	0 sccm
Temperature	300 °C
Chuck height	20 mm



30% AlScN CLMRs - Highest figure of merit SHF Acoustic Resonator





$f_s \cdot Q$ vs. Electromechanical coupling, k_t^2 [%]

$f_s \cdot Q$ vs. Scandium concentration, [%]

$f_s \cdot k_t^2 \cdot Q$ vs. Resonance frequency, [GHz]

$f_s \cdot k_t^2 \cdot Q$ vs. Electromechanical coupling, k_t^2 [%]

- 30% ScAlN resonators from this work (low-T sputtering)
- AlN resonator from NU (low-T sputtering)
- 12% ScAlN resonator from Georgia Tech (epitaxial)

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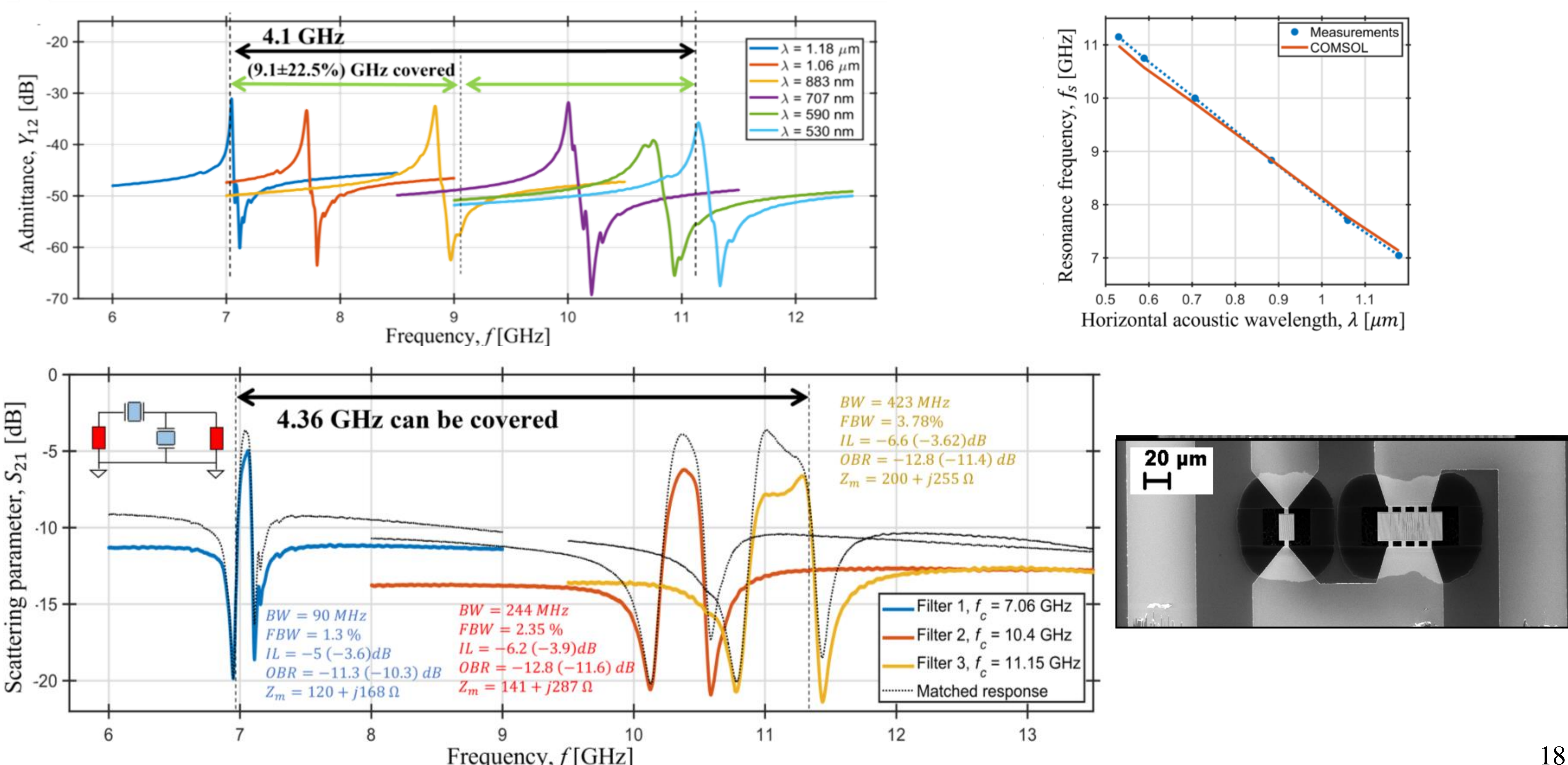
Single-chip Multi-Band SHF $AlSc_{30}N$ Filters



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