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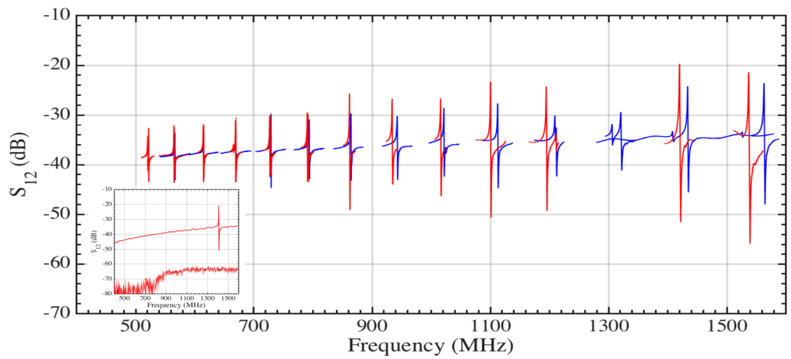

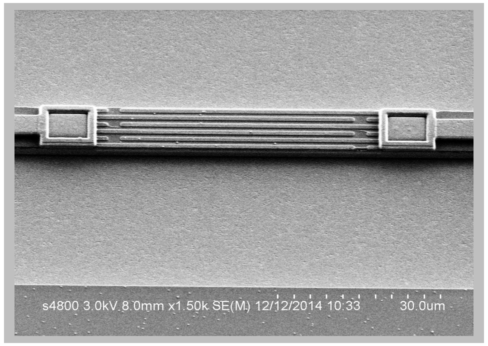

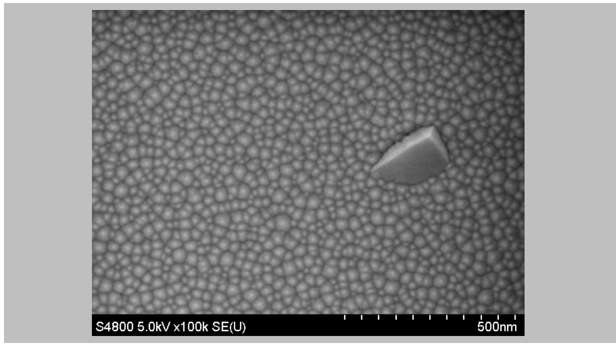

AlN and ScAlN Contour Mode Resonators for RF Filters

M.D. Henry, R.P. Timon, T.R. Young, C.D. Nordquist, B.A. Griffin

U.S. DEPARTMENT OF ENERGY
NNSA National Nuclear Security Administration

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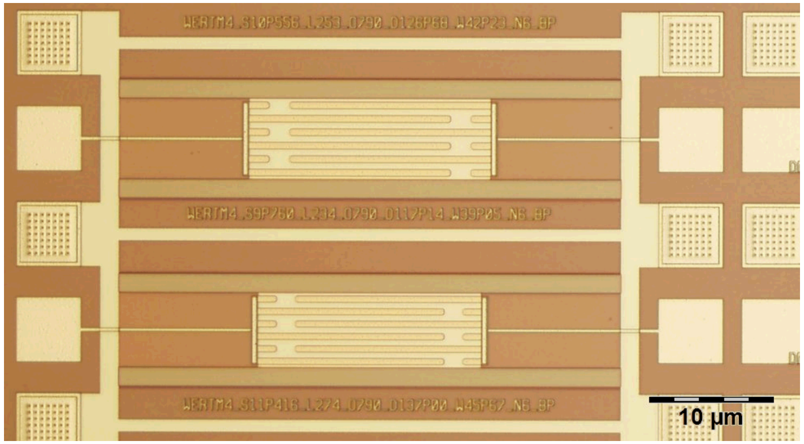
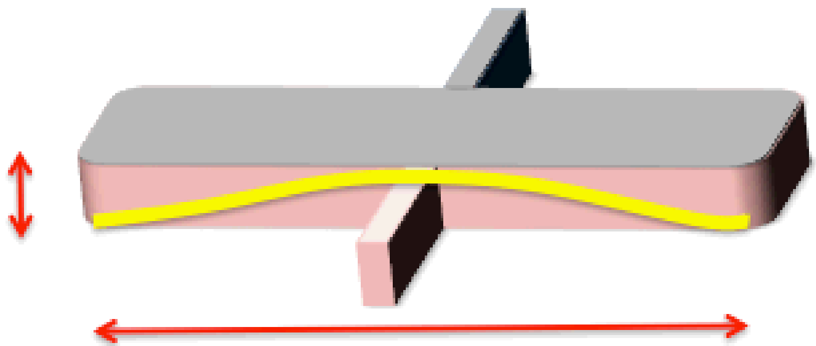
AlN and ScAlN Contour Mode Resonators for RF Filters

- Why Contour mode resonators?
  - How do they work & where are they used
- Role of Sc in AlN
- Development of Single Target $Sc_{0.125}Al_{0.875}N$
- Film Quality and Significant Deposition Issues
- Resonator Performance

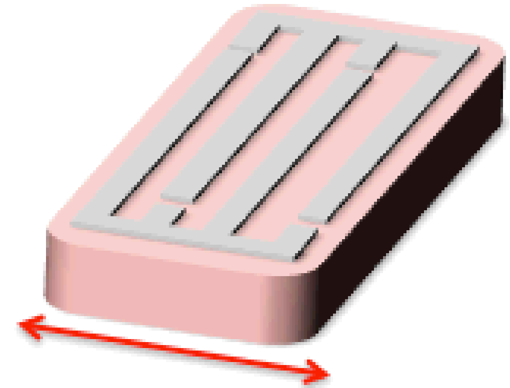


Contour Mode Resonators

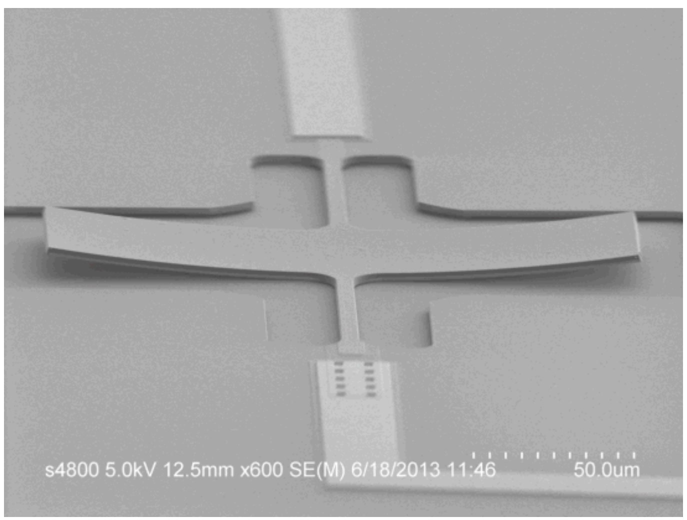
E-Field



Acoustic-wave

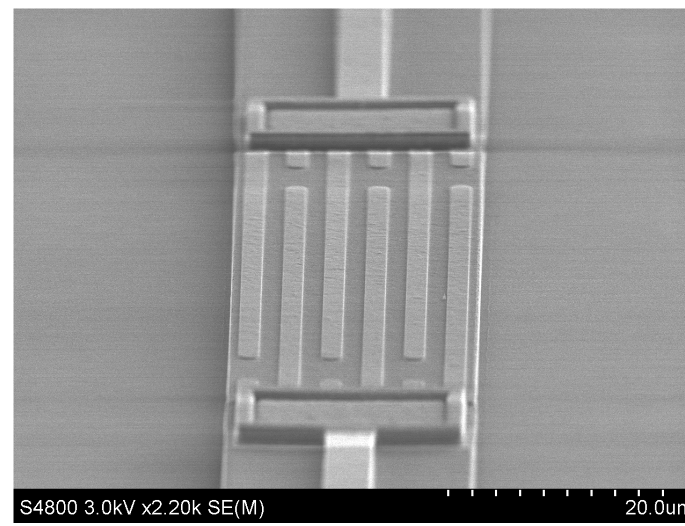


Acoustic-wave



$$f=\frac{v}{\lambda}=\frac{1}{2w}*\sqrt{\frac{\sum E*t}{\sum \rho*t}}$$

$$w=\frac{n\lambda}{2}$$

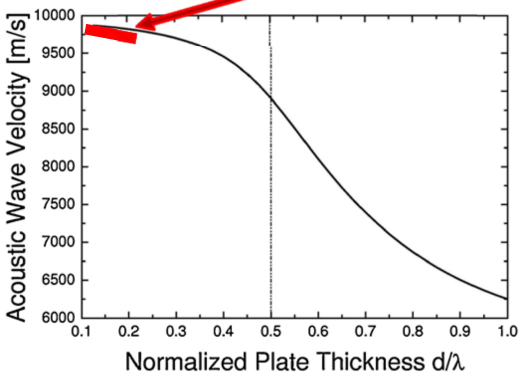


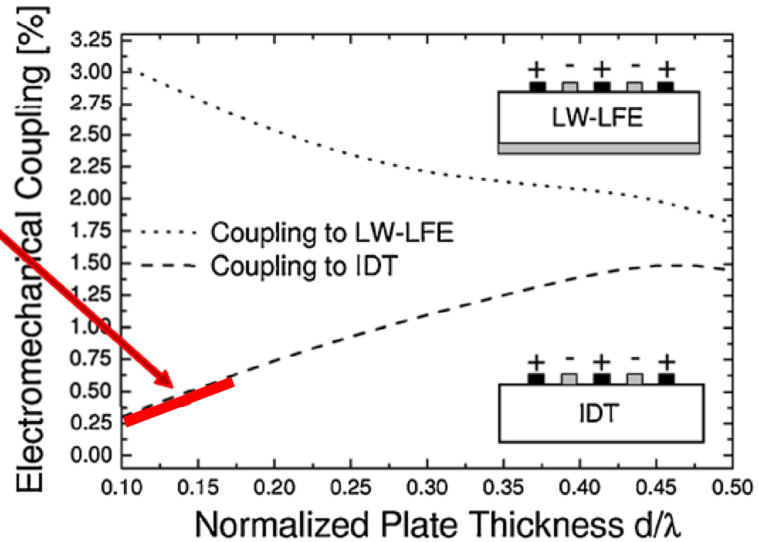
Contour mode resonators take an electric field (z axis) and create an acoustic wave (x axis) using the piezoelectric properties of a film (AlN).

M. D. Henry, J. Nguyen, T. R. Young, T. Bauer, and R. Olsson, "Frequency Trimming of Aluminum Nitride Microresonators Using Rapid Thermal Annealing," *JMEMS,* pp. 1-1, 2013.

Contour Mode Resonators

At 750 nm thick, this work is creating devices 500 MHz to 2 GHz to address RF filter applications.



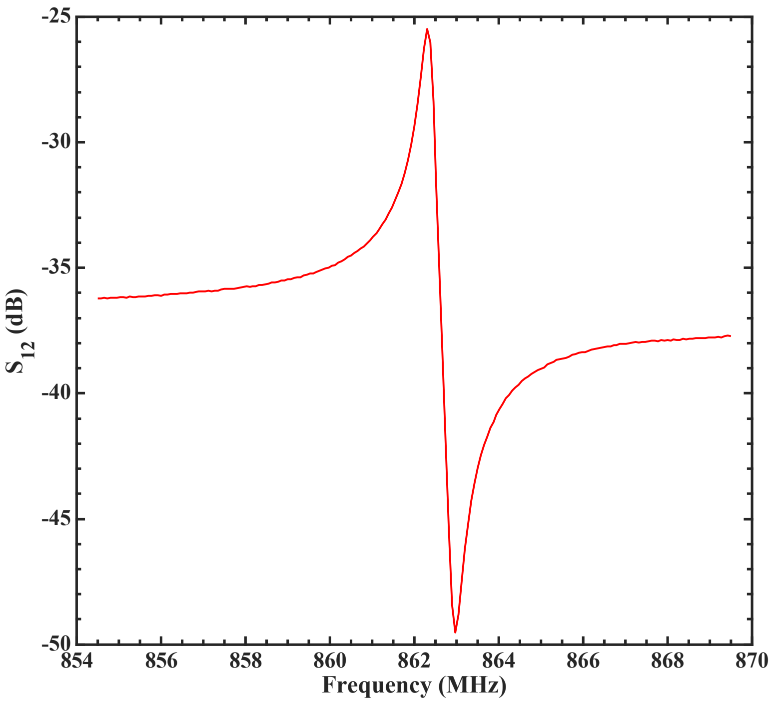


Two fundamental subsets of Lamb-wave Contour mode resonators (CMR) – 1) top electrode interdigitated transducer (IDT) and 2) IDT top electrode with floating lower electrode.

This work utilizes top electrode IDTs, due to the simplicity of rapid fabrication.

V. Yantchev and I. Katardjiev, "Thin film Lamb wave resonators in frequency control and sensing applications: a review," *Journal of Micromechanics and Microengineering,* vol. 23, p. 043001, 2013

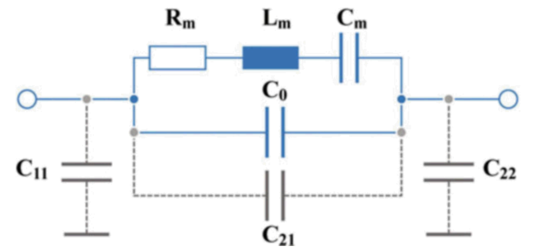
Anatomy of a Resonance



f_s= 862.30 MHz

Δf= 375 kHz

IL(f=f_s)=-25.478 dB



$$Z_{resonator} = \frac{1 + SR_mC_m + S^2L_mC_m}{1 + SR_m(C_m||C_o) + S^2L_x(C_m||C_o)} * \frac{1}{S(C_m + C_o)}$$

f_p= 862.975 MHz

$$Q_L = \frac{F_s}{\Delta f} = 2300$$

$$k_{eff}^2 = \frac{f_p^2 - f_s^2}{f_p^2} = 0.156\%$$

$$FOM = k_{eff}^2 * Q_{UL} = 3.59$$

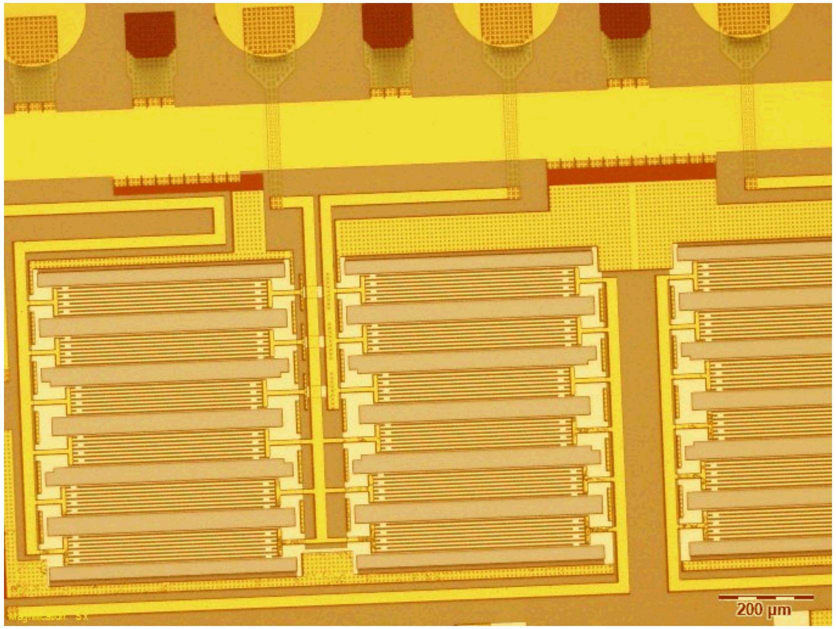
$$Q_{UL} = \frac{Q_L\, R_x}{100 + R_x} = 2178$$

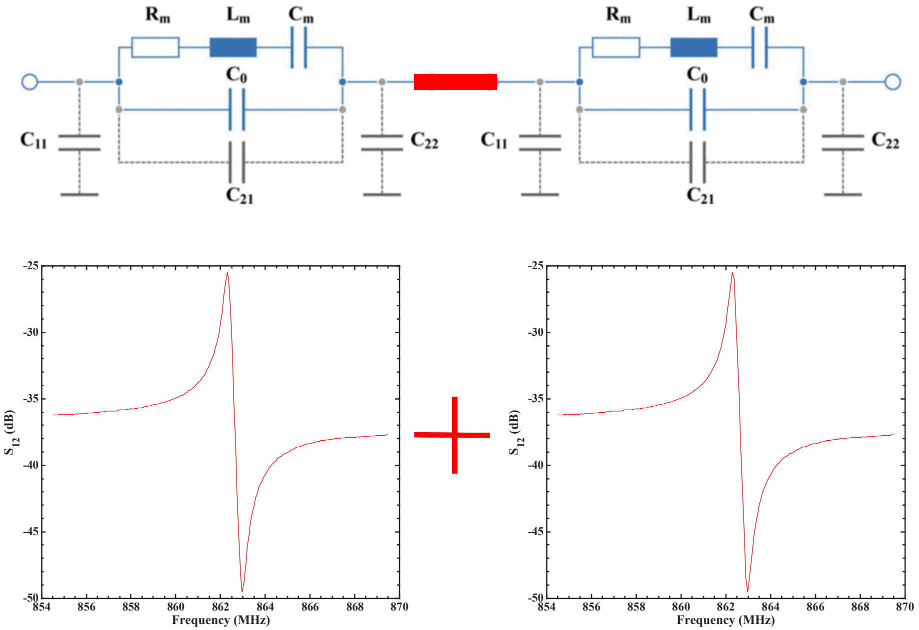
$$k_t^2 = \frac{\pi^2}{8}\,\frac{k_{eff}^2}{1-k_{eff}^2} = \frac{d_{31}^2\, E}{\epsilon} = 0.193\%$$

$$R_x = 100 * (10^{-IL/20} - 1) = 1779\,\Omega$$

J. H. Kuypers, "High Frequency Oscillators for Mobile Devices," in *Piezoelectric MEMS Resonators*, ed: Springer, 2017, pp. 335-385.

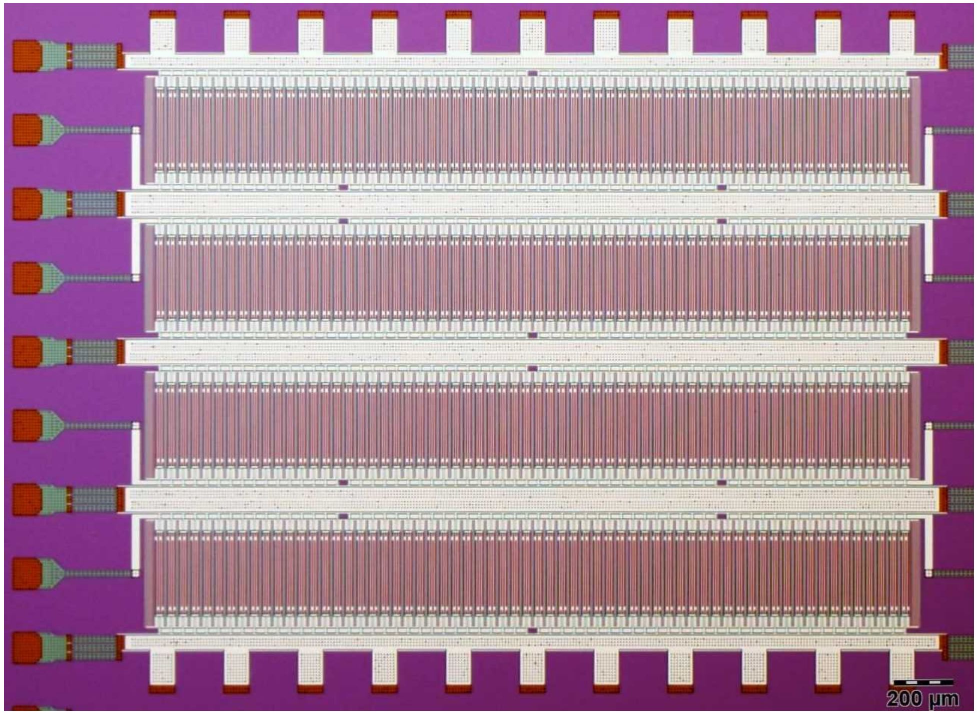
Resonators to RF Filters

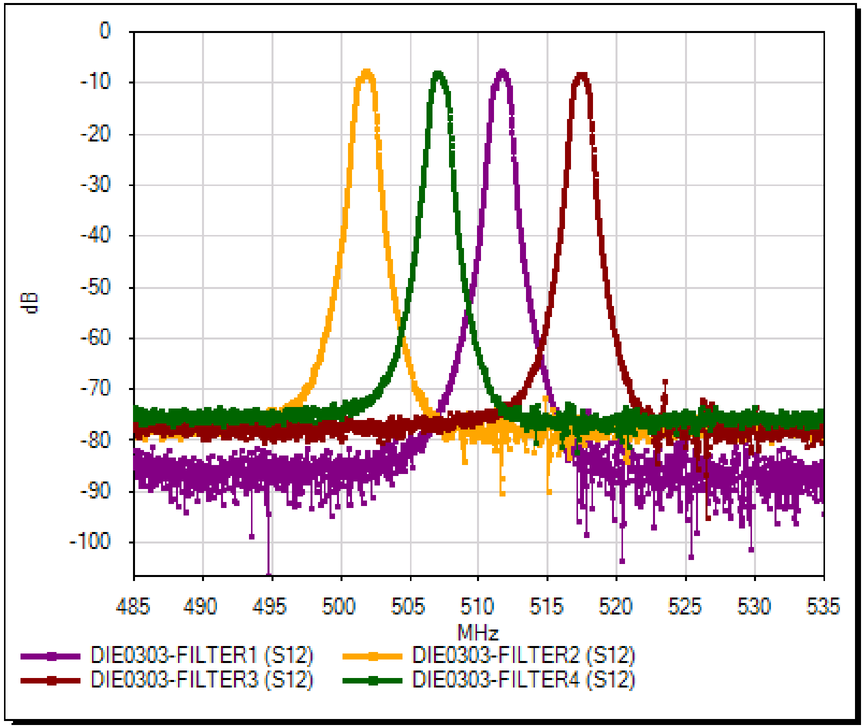




The value proposition for contour mode resonators is that when configured in banks, RF filters can be created.

Resonators to RF Filters

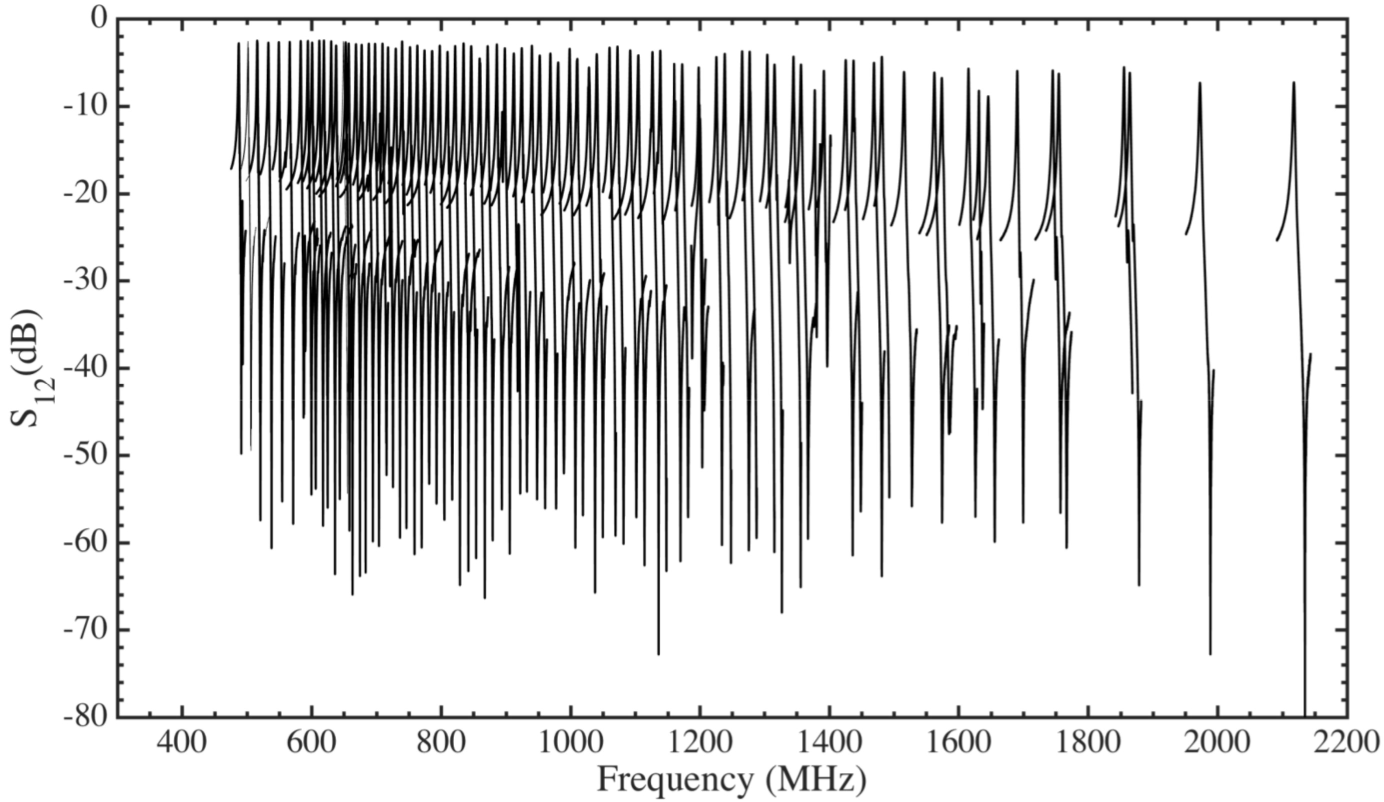


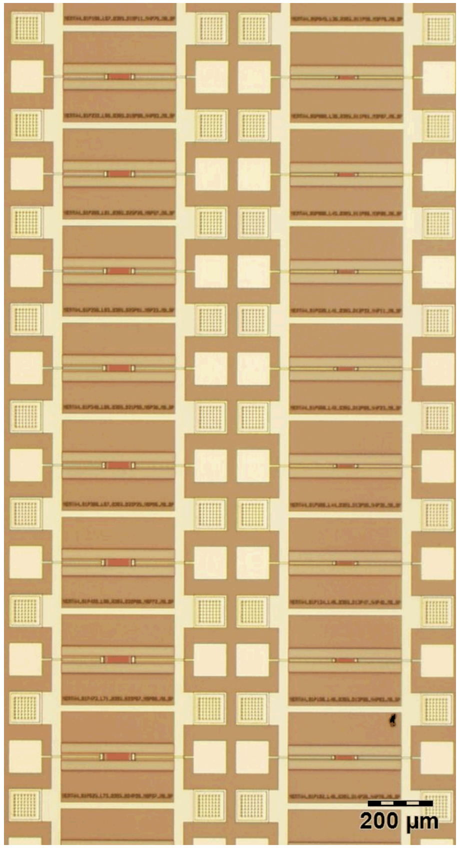


Small changes in the lithographic layout of the CMRs, can control the bandpass frequency. Other piezoelectric device designs require changes to the film thickness; this is less optimal.

M. D. Henry, T. Young, A. E. Hollowell, M. Eichenfield, and R. H. Olsson, "Wafer-level packaging of aluminum nitride RF MEMS filters," presented at the Electronic Components and Technology Conference (ECTC) , 2015 IEEE 65th, San Diego, CA, 2015.

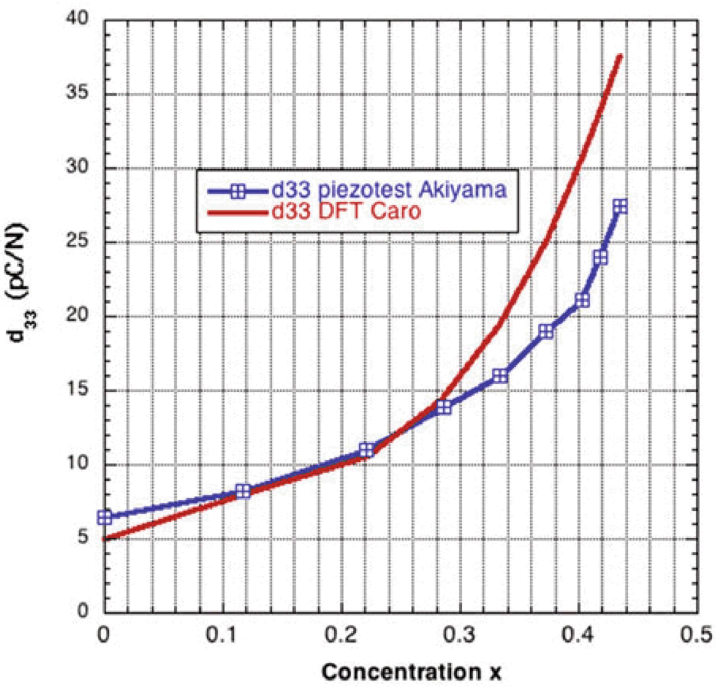
Many Contour Mode Resonators

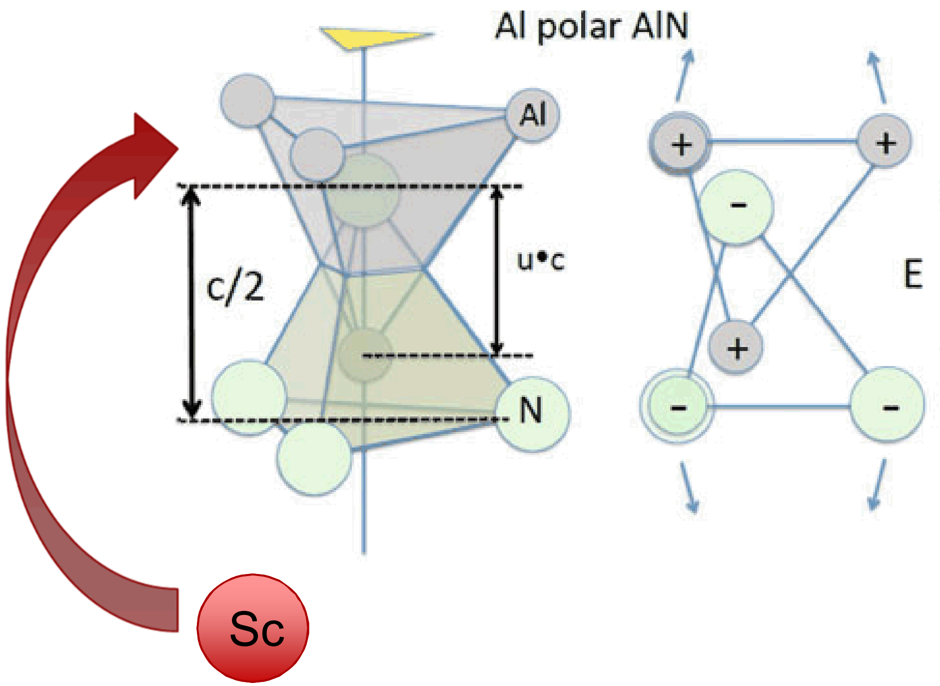




With CMR, a wide range of resonances can be achieved on the same wafer, and on the same die. Above is a die of resonators created in 750 nm thick AlN.

What is the Limitation and Why Sc



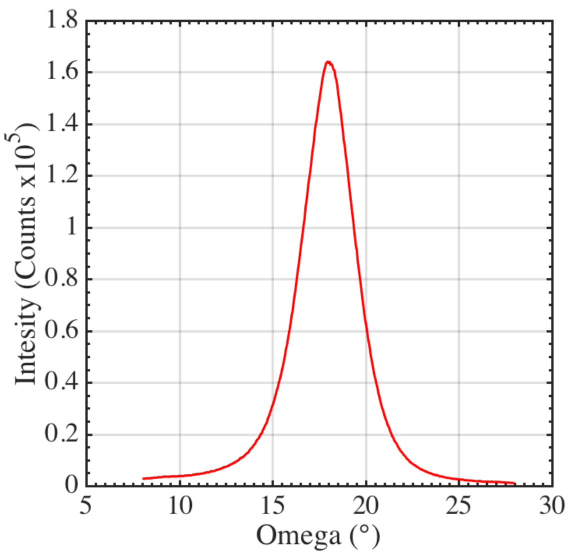


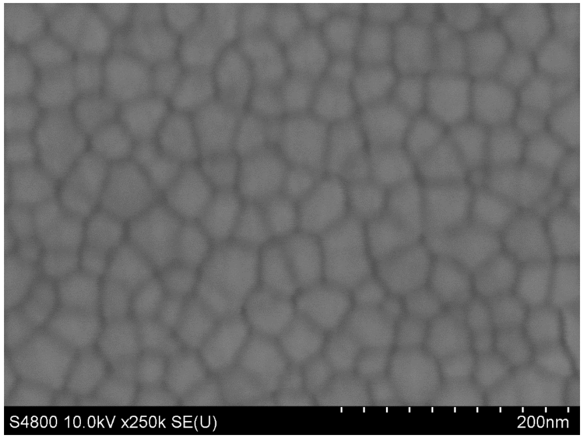
$$k_{eff}^2 = \frac{f_p^2 - f_s^2}{f_p^2} \sim \frac{d_{31}^2 E}{\epsilon}$$

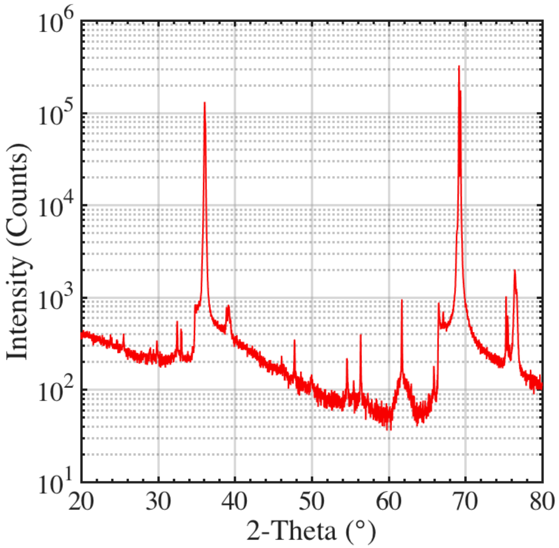
Substitutional replacement of Al with Sc, is expected to increase the ionic displacements in electric fields.

P. Muralt, in *Piezoelectric MEMS Resonators* (Springer, 2017), pp. 3-37.

AlN Film Quality

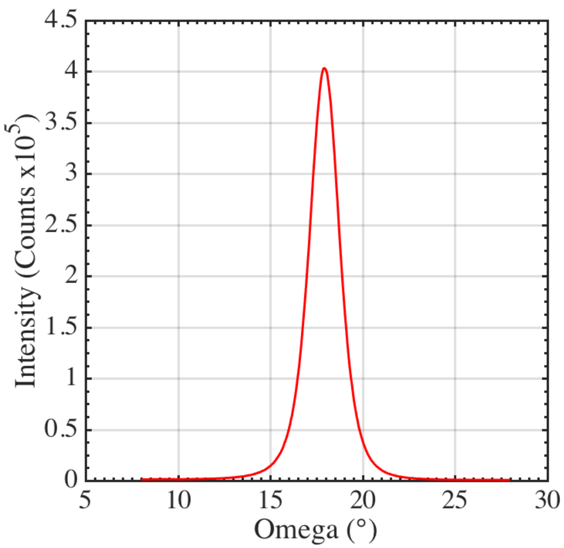


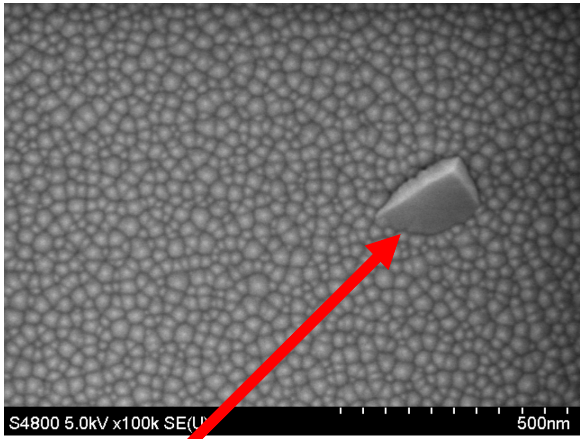


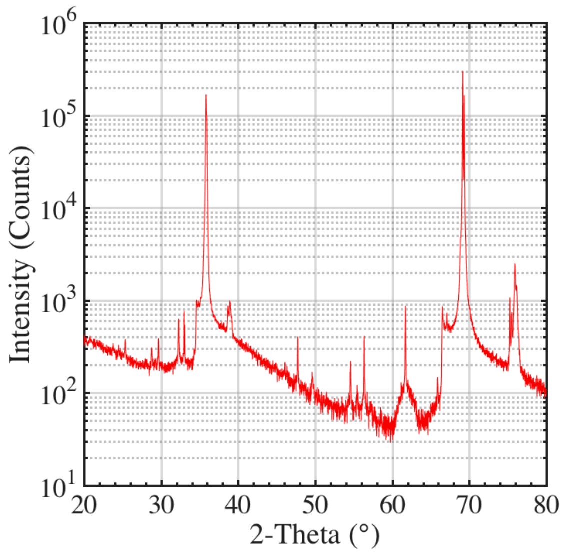


XRD scans of AlN film with a (002) peak located at 36.082° and a rocking curve FWHM of 2.248°.

ScAlN Film Quality



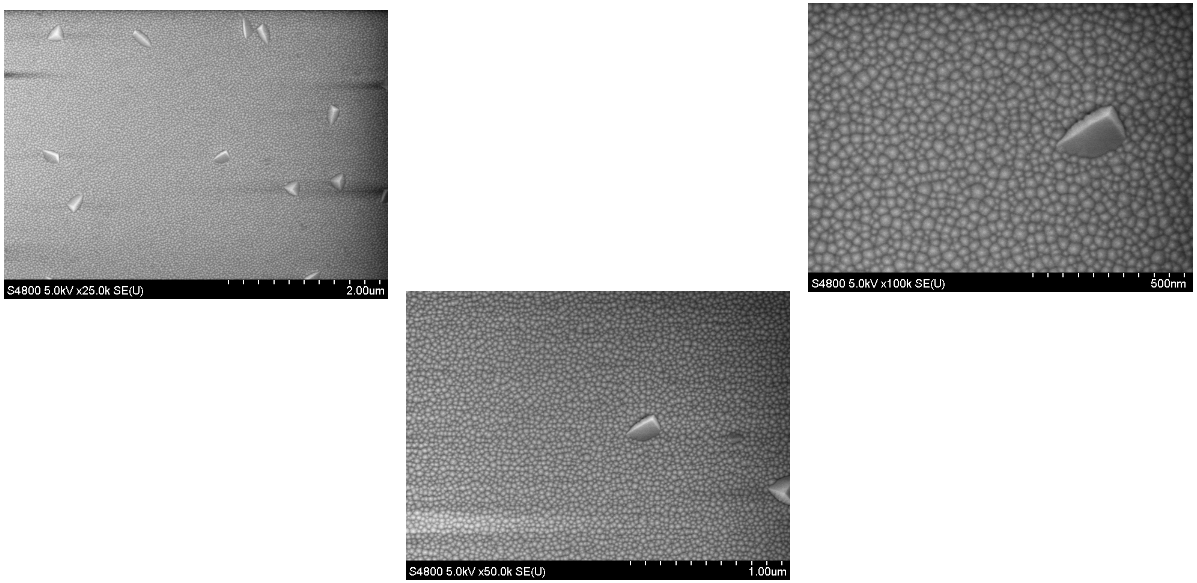




XRD scans of ScAlN film with a (002) peak located at 35.911° and a rocking curve FWHM of 1.906°.

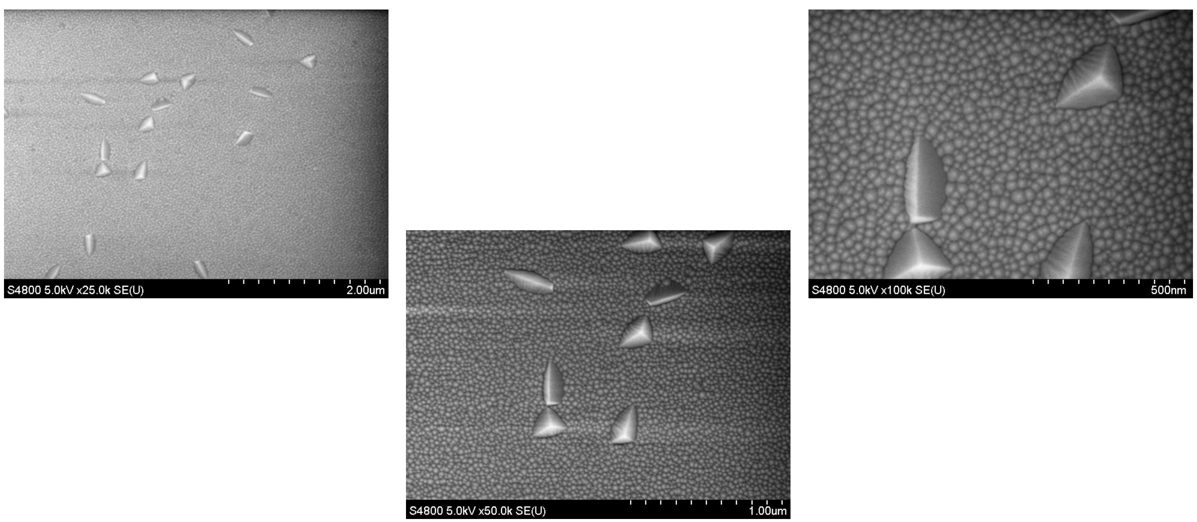
The problem with the film comes out with the SEM.

Inclusions in the ScAlN Deposition



<u>Sigma Deposition conditions</u>:
5kW, 710 sec, 25 sccm Ar, 125 sccm N_2, 82 W RF, 350 C

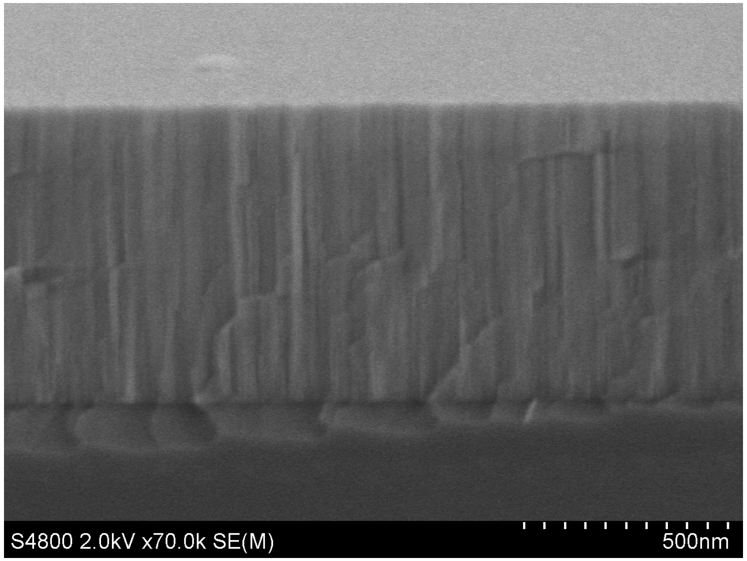
<u>Deposition results:</u>
Stress -58 MPa,
Thickness 737.7 nm, index=2.1500,
θ-2-θ = 1.906°, 1.917°

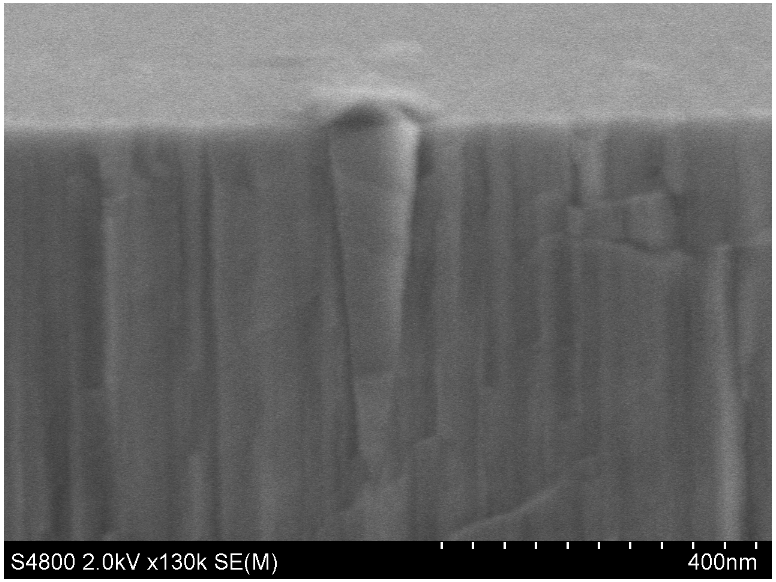


<u>Sigma Deposition conditions</u>:
5kW, 710 sec, 25 sccm Ar, 125 sccm N_2, 82 W RF, 375 C

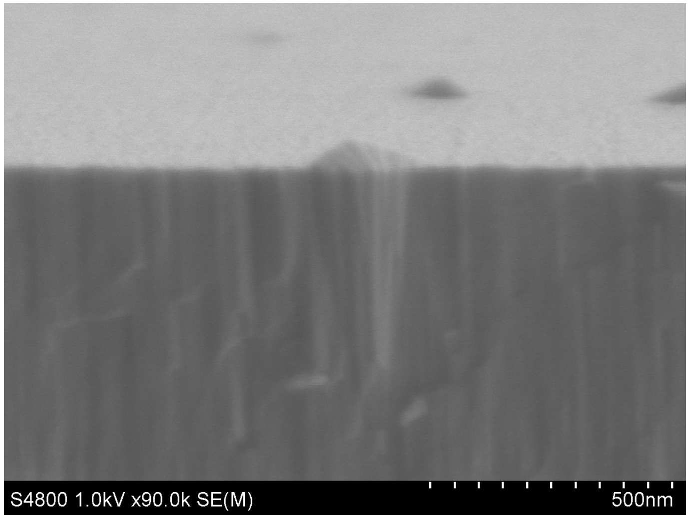
<u>Deposition results:</u>
Stress -27 MPa,
Thickness 738.5 nm, index=2.1499,
θ-2-θ = 1.894°, 1.899°

Inclusions in the ScAlN Deposition

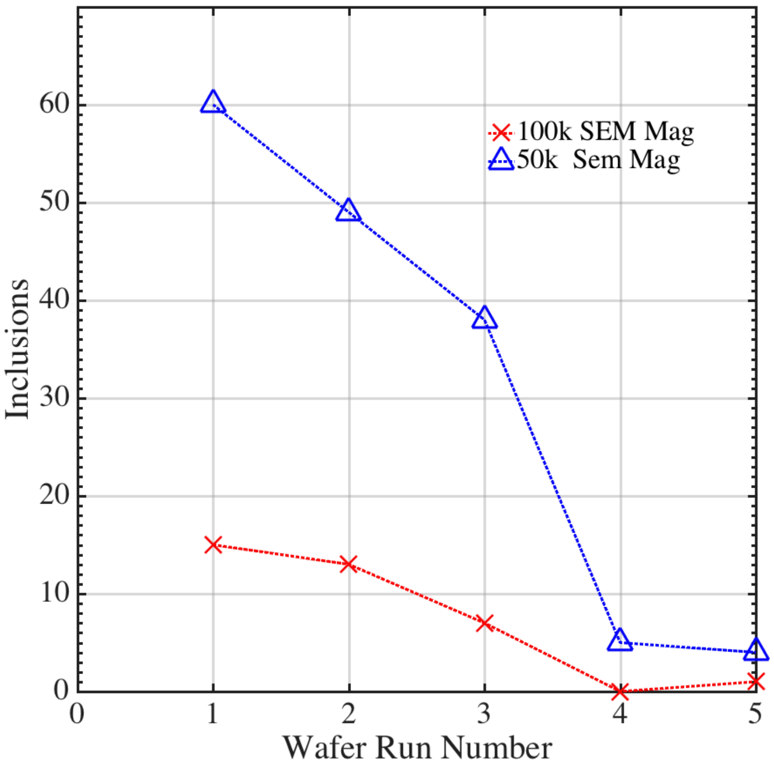




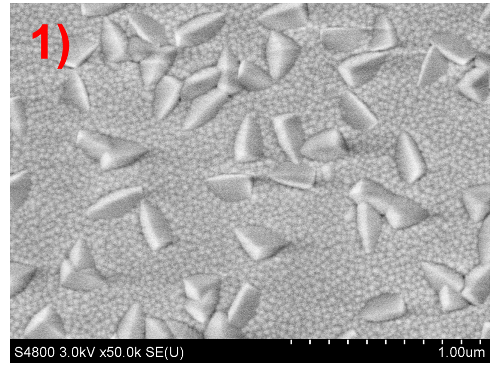
SEM suggests aligned grain structure, from a cleave. The inclusions also appear aligned with the majority of the film.

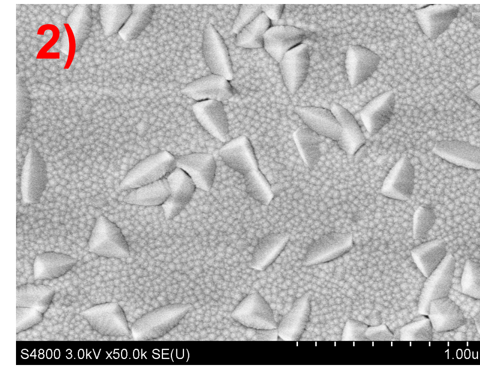


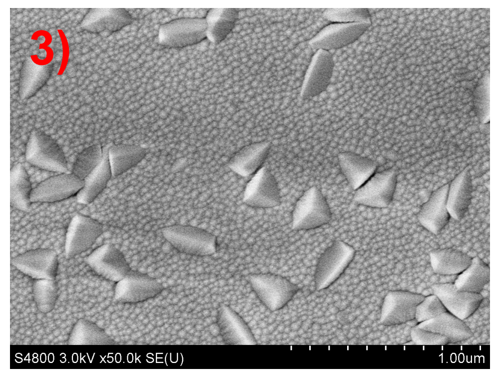
Mitigation of Inclusions – Baffles

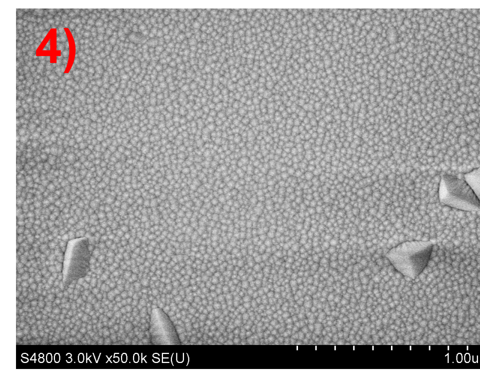


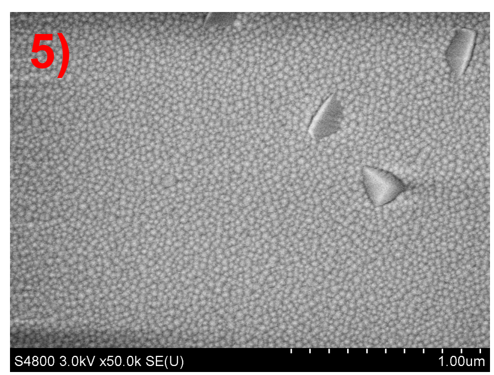
For a cassette load of wafers, running 4 to 5 dummys ahead of the device wafers drives the inclusion count to acceptable levels. This suggests conditioning of the target or residual gas (maybe loadlock) is needed to eliminate species.



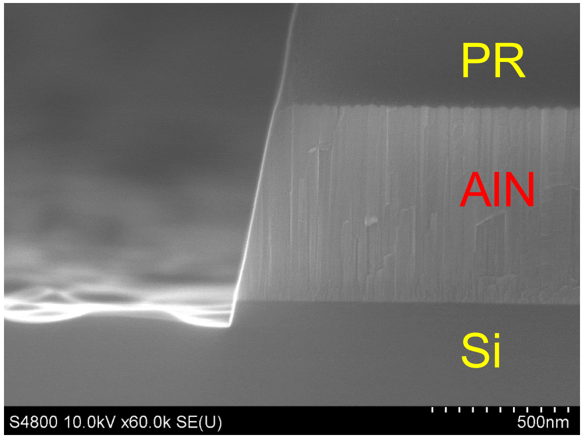






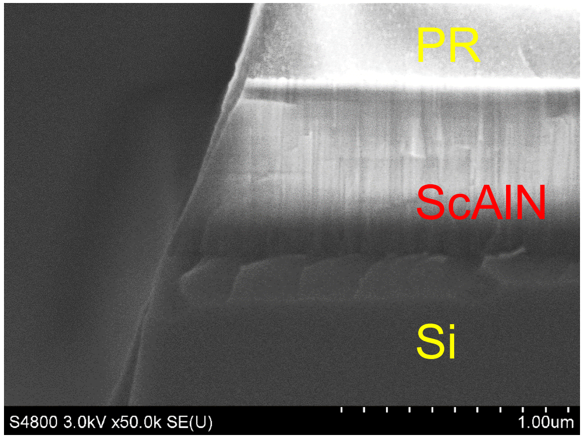


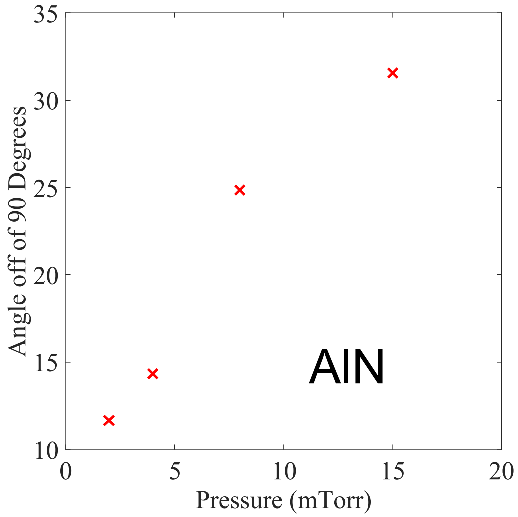
Plasma Etch is Challenging



<u>PlasmaTherm ICPRIE</u> :
ICP (2 MHz) – 1000 W
Bias (13.56 MHz) - 200 W
Gas – BCl_3 30 sccm, Cl_2 12 sccm
Pressure 1.7 mTorr

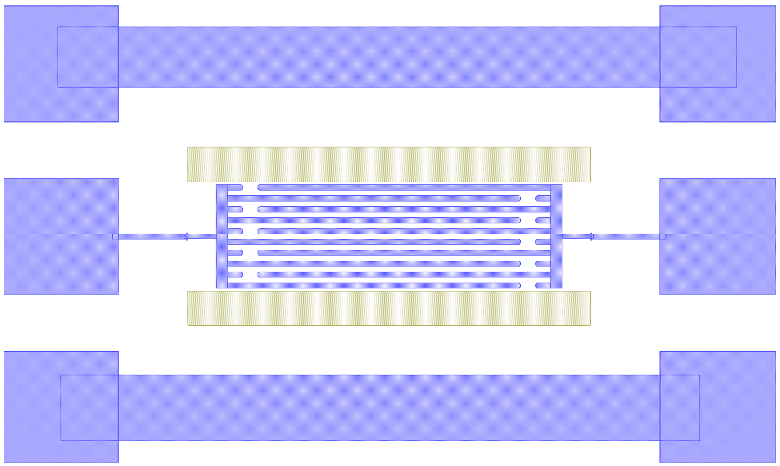
AlN ER – 331 nm/min
ScAlN ER – 97.7 nm/min

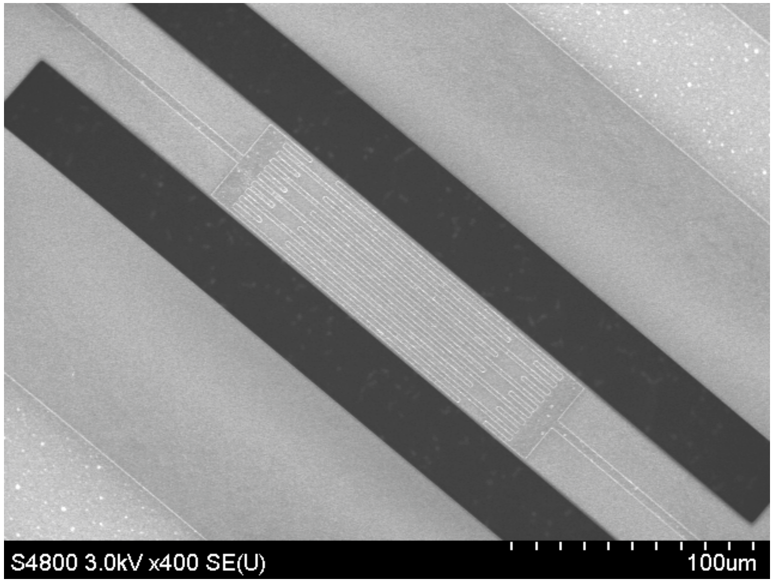




Control over the sidewall angle is controlled by the chamber pressure.

Fabrication of a Resonator

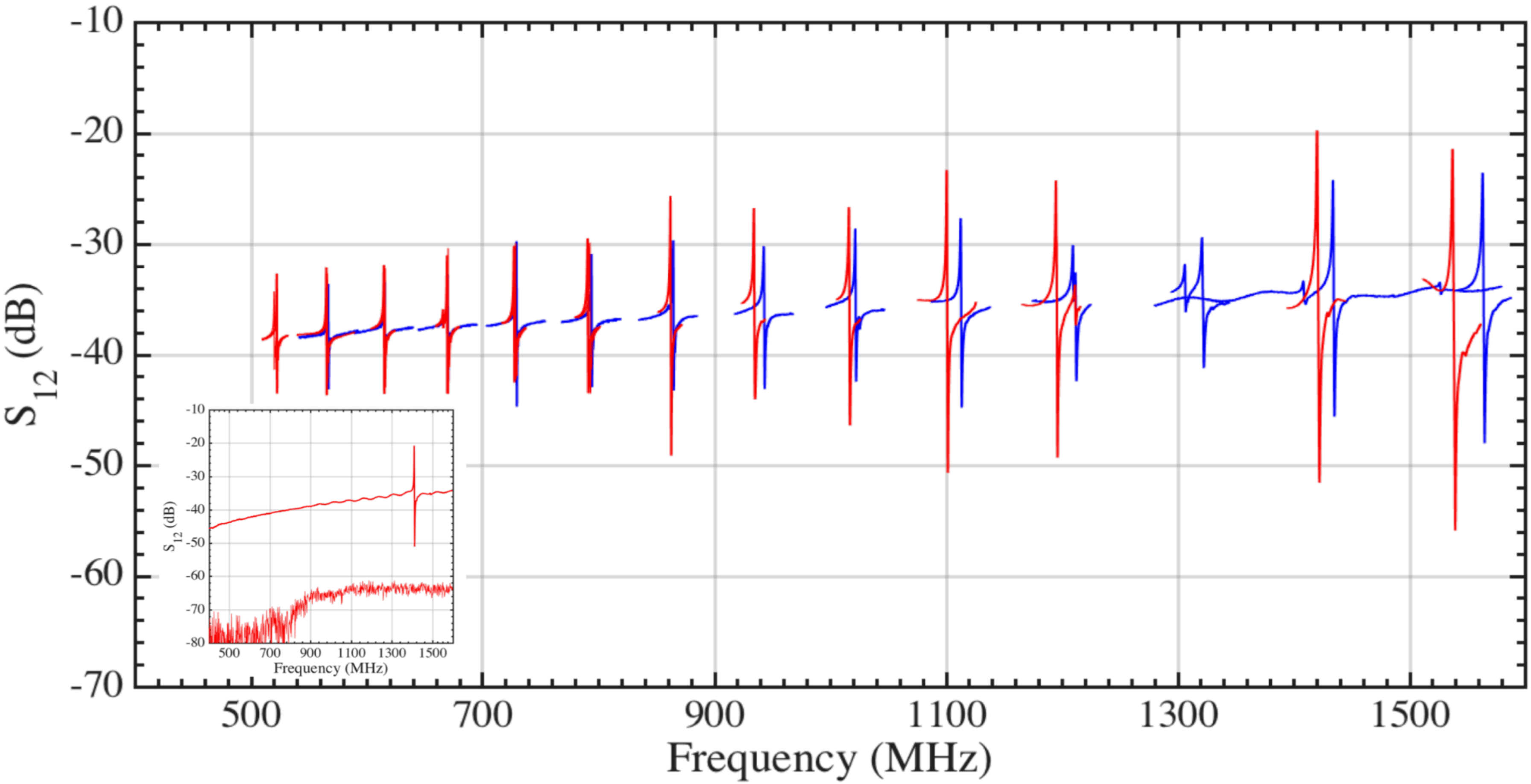




Fabrication Sequence:

1) Deposit ScAlN
2) Deposit Al (top metal)
3) Stepper pattern Al IDT & Etch
4) Stepper pattern ScAlN & Etch
5) XeF_2 to release resonator

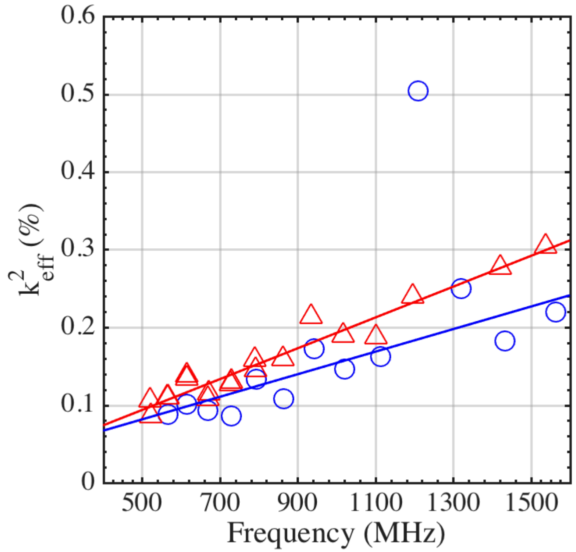
Top Metal IDT CMR Performance

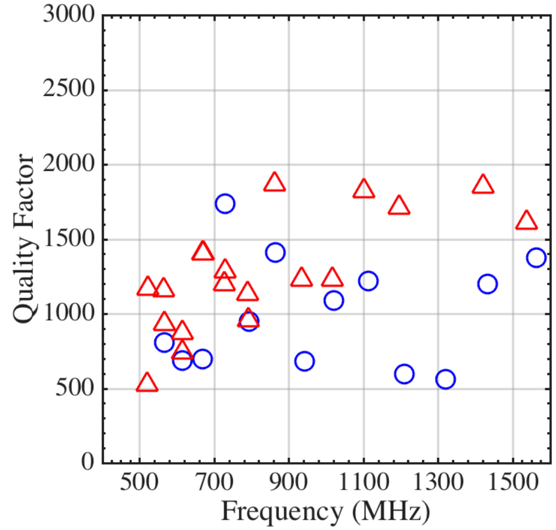


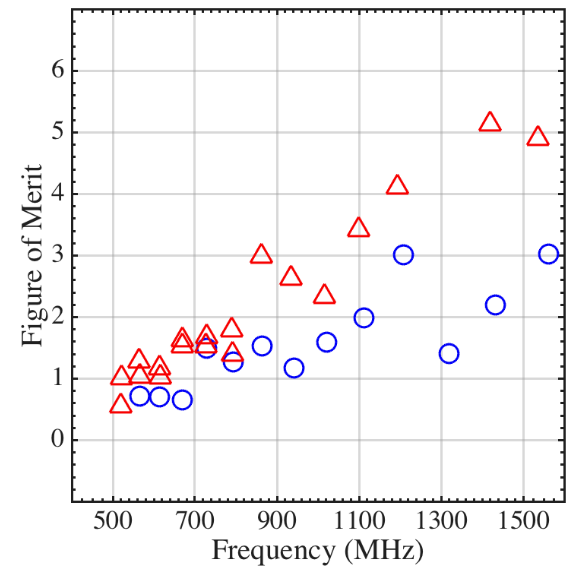
Red is the ScAIN resonators and blue is AIN. A clear improvement in resonator Q and k^2_{eff} is visible.

Measured acoustic velocity in ScAIN = 9860 m/sec.

Top Metal IDT CMR Performance







ScAlN (red triangles) had a 33% improvement in the k2eff over standard AlN (blue circles). Quality factors improved despite the inclusions but is not attributed to improved fabrication.

FOM suggests that improvements can be had with 12.5% Sc substitution.

Next Moves…

- Characterize film deposition – what controls the inclusions, how to get inclusion number down with low compressive to tensile stress
- Why do the inclusions arise?

- **Deposition on BOTTOM METAL!** This will get the k^2_{eff} up to film limitations.

- New ScAlN targets with higher [Sc].