Etching (and Other Important Aspects) of AlScN Materials

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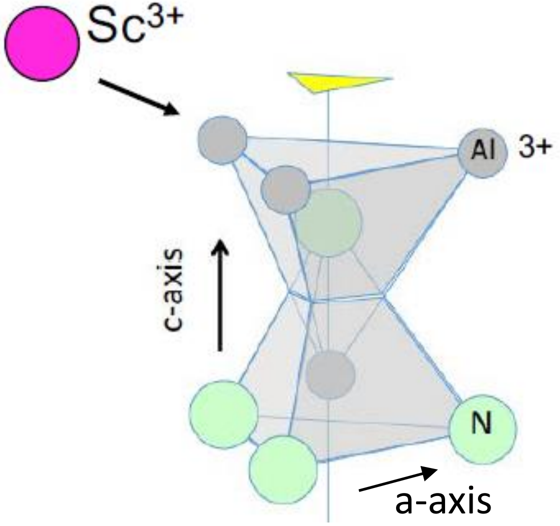
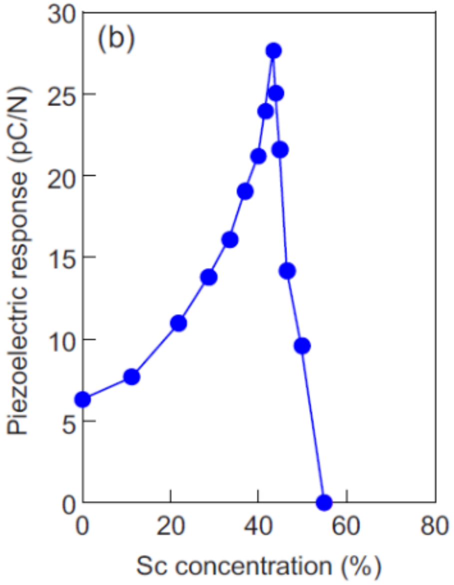
Department of Electrical and Systems Engineering
University of Pennsylvania

Why Aluminum Scandium Nitride?



P. Muralt, “Doped AlN: Materials and devices,” Tutorial IFCS-EFTF 2019.

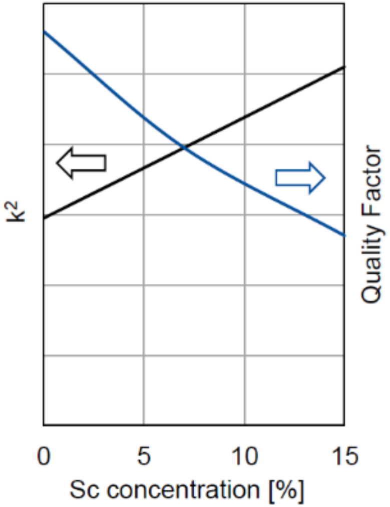


M. Akiyama, K. Kano and A. Teshigahara, “Influence of growth temperature and scandium concentration on piezoelectric response of scandium aluminum nitride alloy thin films,” Appl. Phys. Lett. 95, 162107, 2009.

- AlScN
  - Alters the c/a ratio of the AlN unit cell
  - Large increase in the piezoelectric coefficients
  - Potential to substantially widen the bandwidth of BAW filters

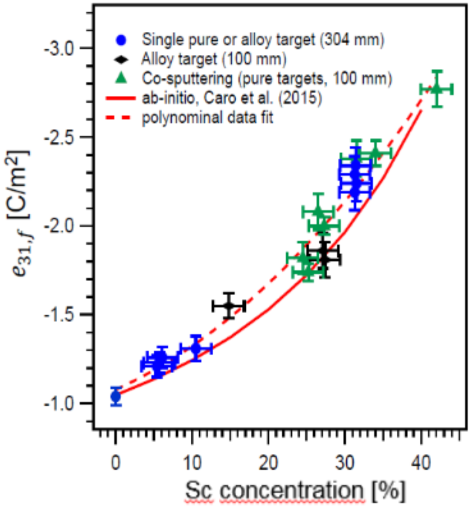
Figure of Merit for Different Piezoelectric Applications

B. Heinz, “The growth of piezoelectric Al(1-x)ScxN thin films on Si (100) and Pt (111) using co-sputtering and compound target sputtering,” IEEE NEMS, April 2018.



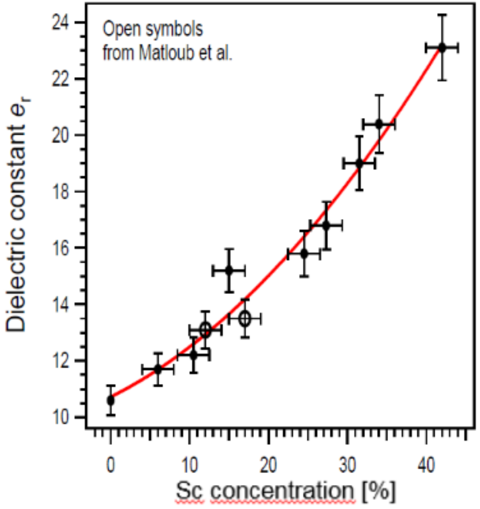
FOM for RF resonator applications

$$\frac{d_{33}^2 E}{\varepsilon_0 \varepsilon_r} \times Q$$



Signal to noise FOM for MEMS sensors

$$\frac{e_{31,f}}{\sqrt{\epsilon_0 \epsilon_r \cdot \tan(\delta)}}$$

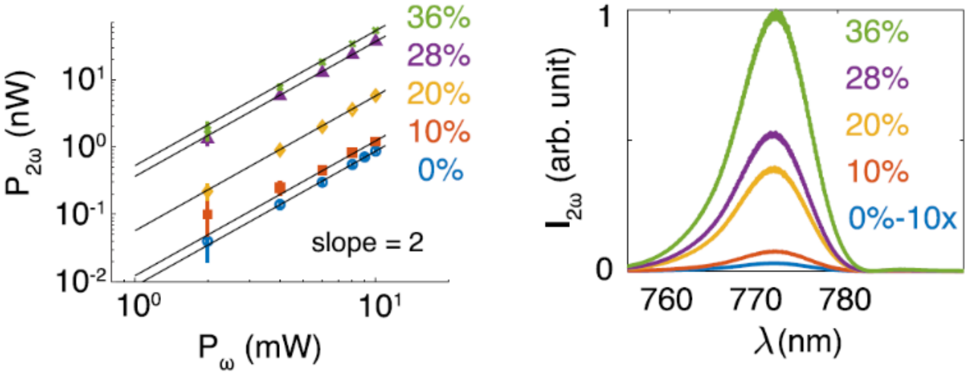


Energy FOM

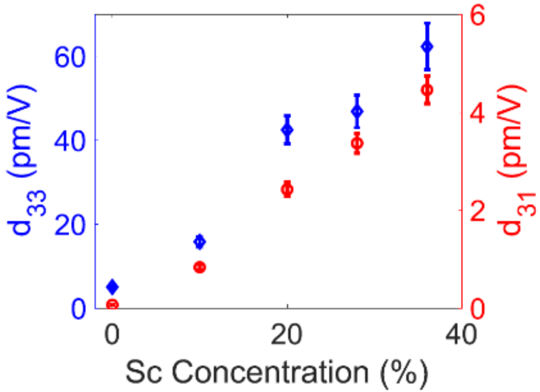
$$\frac{e_{31,f}^2}{(\epsilon_0 \epsilon_r)}$$

AlScN Nonlinear Optics (Collaboration with Bo Zhen)

- A strongly nonlinear optical material that can be grown directly on Si
- Ferroelectric properties allowing for periodic poling
- Nonlinear optical coefficients larger than $LiNbO_3$
- Next step is to investigate lower optical loss formulations



2nd Harmonic Generation in AlScN for different Sc alloying



Measured nonlinear optical coefficients

V. Yoshioka, J. Lu, Z. Tang, J. Jin, R. H. Olsson III, and B. Zhen, "Strongly Enhanced Second-Order Optical Nonlinearity in CMOS-Compatible $Al_{1-x}Sc_xN$ Thin Films," *APL Materials*, 9, 101104, October 2021.

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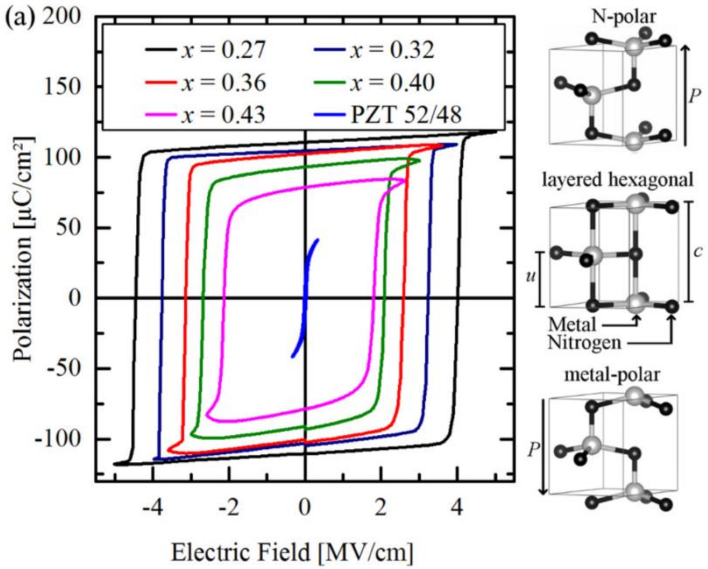
Ferroelectric Properties of AlScN

[1] Phys. Status Solidi A 2020, 217, 1900840

Material	P_r (μC/cm²)	E_c (MV/cm)	T_{MAX} (°C)	CMOS BEOL
AlScN	80-130	2-6.5	350	Yes
$HfZO_2$ [1]	5-24	1.3	400	Yes
PZT	20-40	0.05	> 600	No

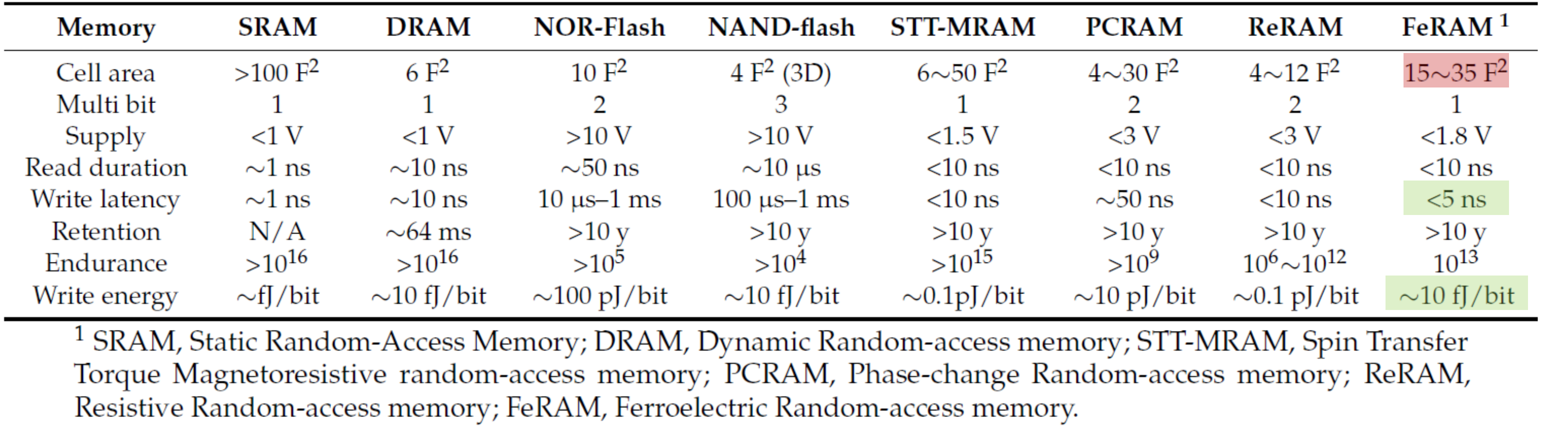
- Polar and ferroelectric as deposited w/ minimal wakeup
- Only two available polarization states
- Sharp ferroelectric switching
- Large remanent polarization and coercive field
- Low temperature deposition but stable polarization to extremely high temperatures (1100 °C)
- Initial reported results for films ~500 nm requiring >100V to switch



S. Fichtner, N. Wolff, F. Lofink, L. Kienle, and B. Wagner, "AlScN: A III-V semiconductor based ferroelectric", *J. Appl. Phys.* 125, 114103 (2019)

Memory Comparison and Motivation

H. Cai et al., “High performance MRAM with spin-transfer-torque and voltage-controlled magnetic anisotropy effects,” *Appl. Sci.*, 7, 929 (2017)



Memory	SRAM	DRAM	NOR-Flash	NAND-flash	STT-MRAM	PCRAM	ReRAM	FeRAM [1]
Cell area	>100 F^2	6 F^2	10 F^2	4 F^2 (3D)	6∼50 F^2	4∼30 F^2	4∼12 F^2	15∼35 F^2
Multi bit	1	1	2	3	1	2	2	1
Supply	<1 V	<1 V	>10 V	>10 V	<1.5 V	<3 V	<3 V	<1.8 V
Read duration	∼1 ns	∼10 ns	∼50 ns	∼10 µs	<10 ns	<10 ns	<10 ns	<10 ns
Write latency	∼1 ns	∼10 ns	10 µs–1 ms	100 µs–1 ms	<10 ns	∼50 ns	<10 ns	<5 ns
Retention	N/A	∼64 ms	>10 y	>10 y	>10 y	>10 y	>10 y	>10 y
Endurance	>10^{16}	>10^{16}	>10^5	>10^4	>10^{15}	>10^9	10^6∼10^{12}	10^{13}
Write energy	∼fJ/bit	∼10 fJ/bit	∼100 pJ/bit	∼10 fJ/bit	∼0.1pJ/bit	∼10 pJ/bit	∼0.1 pJ/bit	∼10 fJ/bit

[1] SRAM, Static Random-Access Memory; DRAM, Dynamic Random-access memory; STT-MRAM, Spin Transfer Torque Magnetoresistive random-access memory; PCRAM, Phase-change Random-access memory; ReRAM, Resistive Random-access memory; FeRAM, Ferroelectric Random-access memory.

- **Ferroelectric NVM offers the advantages of low write energy/current and fast read/write speed**
- **The overwhelming weakness of FE NVM is cell area or bit density**
- **We seek to exploit the FE properties of AlScN and its compatibility with CMOS to scale the bit density of FE NVM**
- **To achieve CMOS compatible write voltages will require AlScN thicknesses on order of 10 nm**

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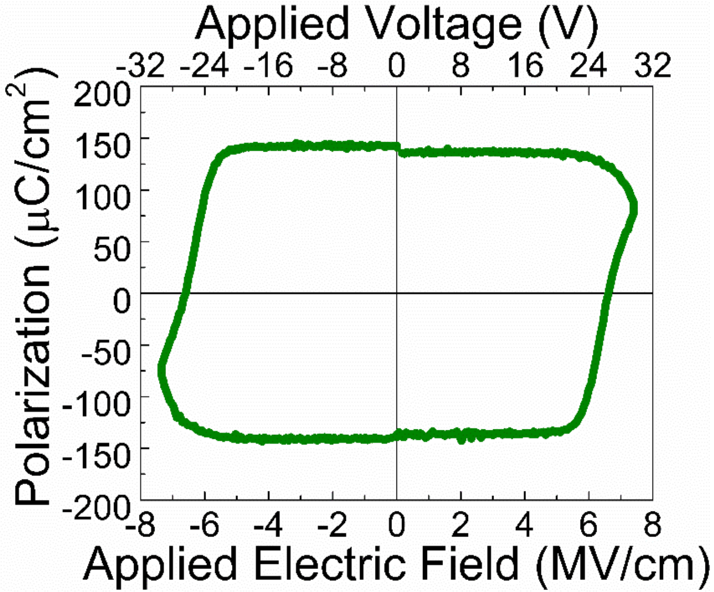
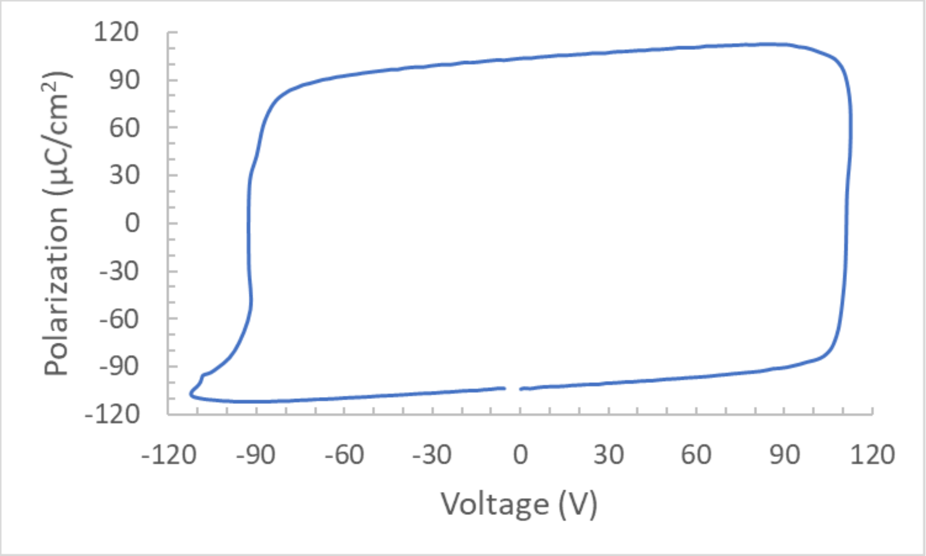
Ferroelectric AlScN Materials



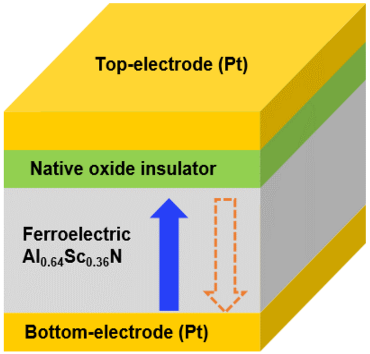
Ferroelectric P-E Loop Measured in a 20 nm Thick $Al_{68}Sc_{32}N$ film

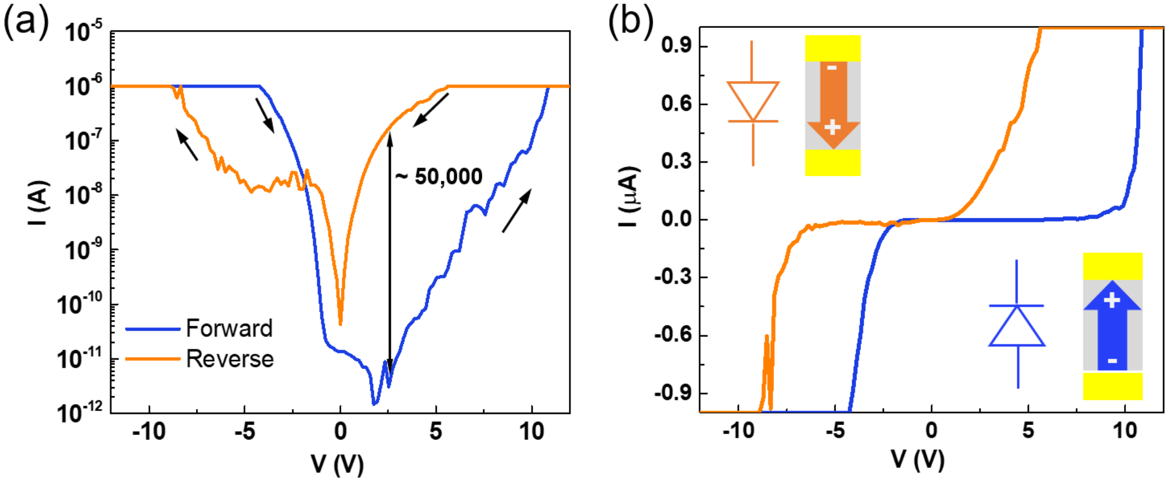


Ferroelectric P-E Loops Measured in a 200 nm Thick $Al_{68}Sc_{32}N$ film

D. Wang, J. Zheng, P. S. M. Gharavi, W. Zhu, A. Foucher, S. E. Trolier-McKinstry, E. A. Stach, and R. H. Olsson III, "Ferroelectric Switching in Sub-20 nm Aluminum Scandium Nitride Thin Films," *IEEE Electron Device Letters*, vol. 41, no. 12, pp. 1774-1777, Dec. 2020.

AlScN Ferroelectric Diodes (Collaboration with Deep Jariwala)



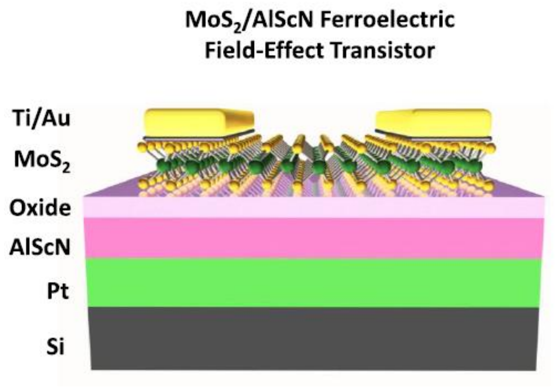


I-V response of ferro-diode realized in 20 nm thick AlScN

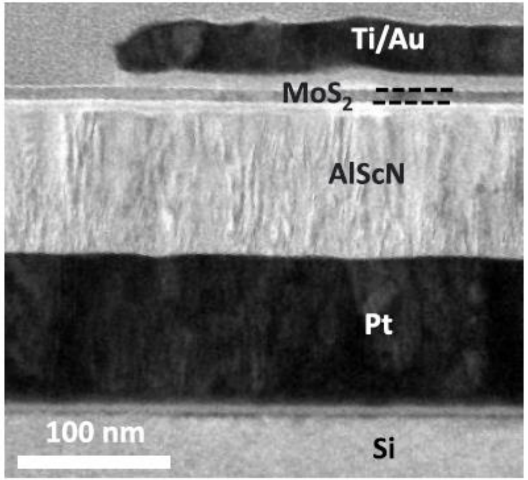
- Ratio of resistance between two different memory states is very large > 10^4
- Inverting diode polarity like behavior observed in forward vs reverse sweeps
- Can be Set/Reset with 1 microamp current

X. Liu et. al, “Aluminum Scandium Nitride based Metal-Ferroelectric-Metal Diode Memory Devices with High On/Off Ratios,” *Applied Physics Letters*, 118, 202901 (2021)

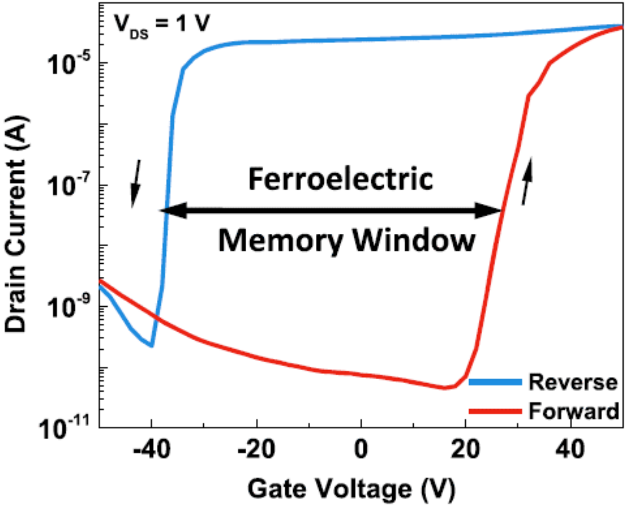
AlScN/MOS$_2$ Ferroelectric FETs (Collaboration with Deep Jariwala)



FeFET device structure



FeFET TEM image

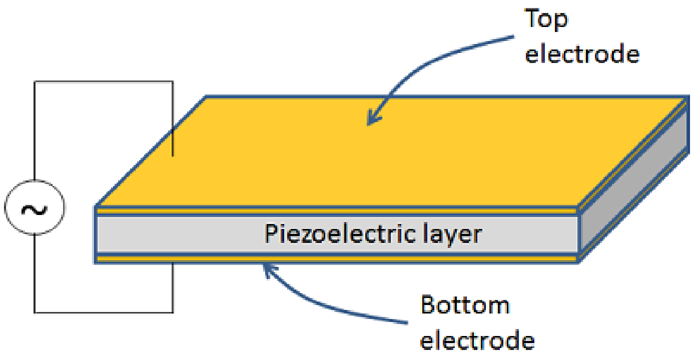


FeFET I_{DS}-V_{GS} hysteresis loop

X. Liu et al., "Post-CMOS Compatible Aluminum Scandium Nitride/2D Channel Ferroelectric Field-Effect-Transistor Memory," *Nano Lett.*, pp. A-I, April 2021.

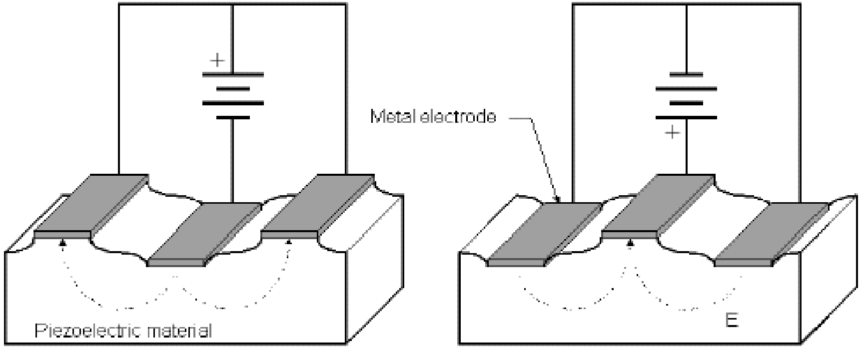
Piezoelectric Resonators and Filters

Bulk Acoustic Wave



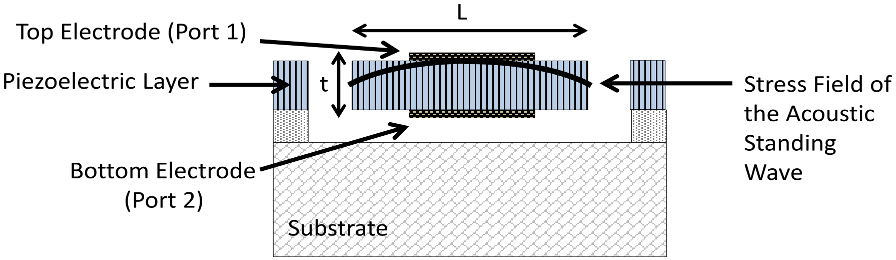
Source: C. Cassella, Course notes from ECEE7398 at NEU

Surface Acoustic Wave

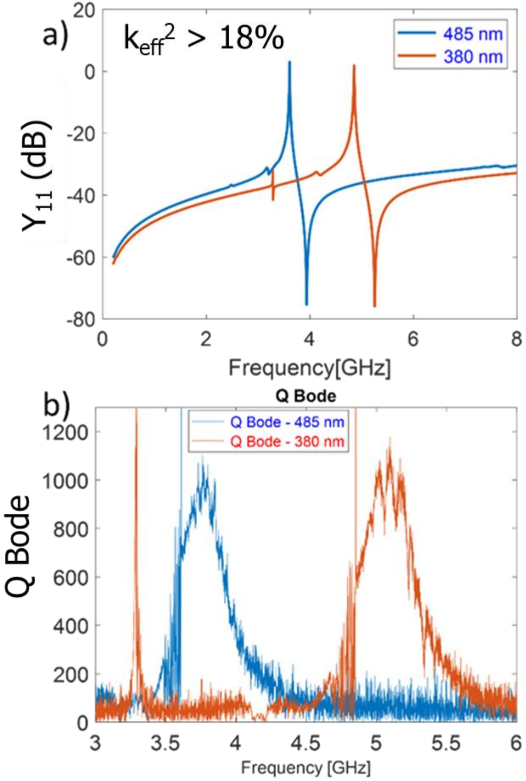


Source: D. Malocha , Intro to Surface Acoustic Wave Technology

Lamb Wave/Contour Mode

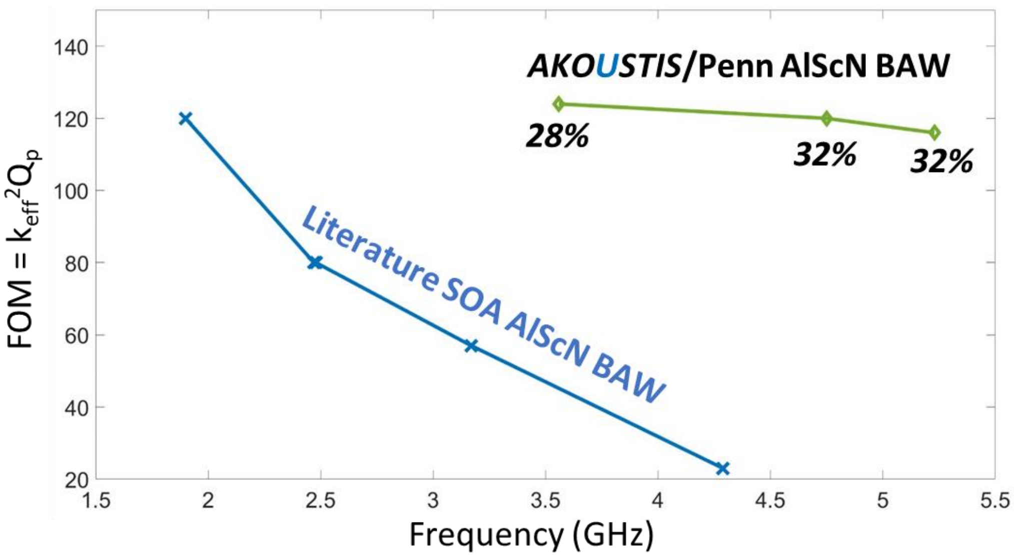


AlScN Bulk Acoustic Wave Resonators



$Al_{68}Sc_{32}N$ BAW Resonator Measurements

- Akoustis BAW resonators constructed from Penn AlScN materials exhibit SOA performancee at high frequency



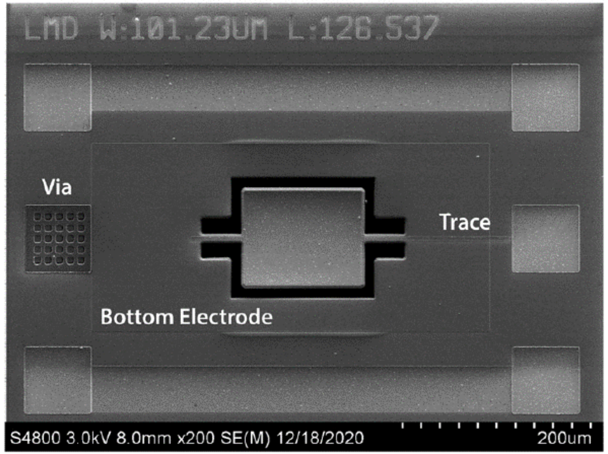
AlScN BAW Resonator Comparison

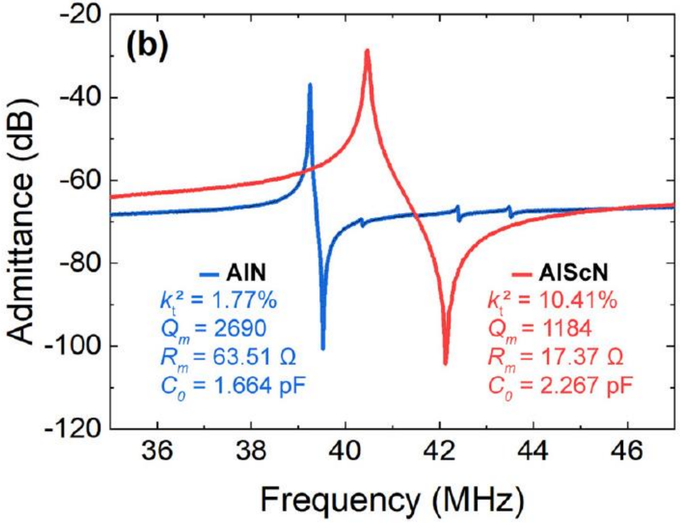
R. Beaucejour, V. Roebisch, A. Kochhar, C. Moe, D. Hodge and R. H. Olsson III, “Controlling Residual Stress and Suppression of Anomalous Grains in Aluminum Scandium Nitride Films Grown Directly on Silicon,” *IEEE JMEMS*, Accepted

High Performance AlScN Piezoelectric MEMS Resonators

Collaboration with Sandia

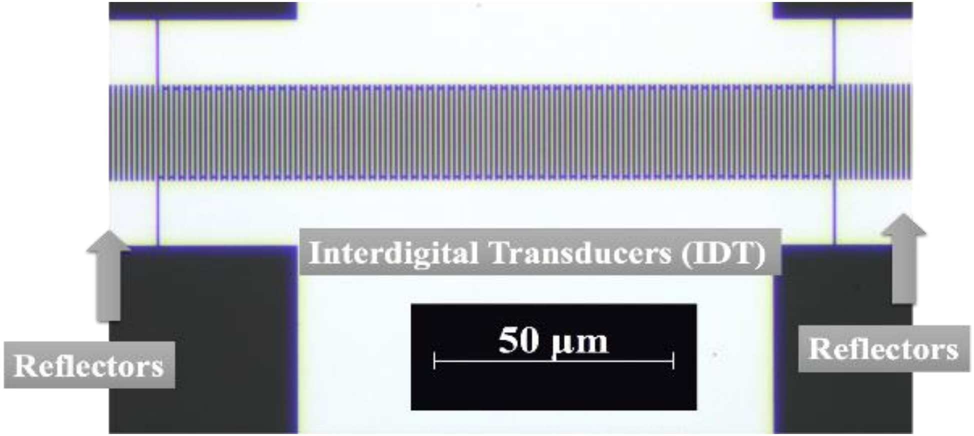
Fabricated Device

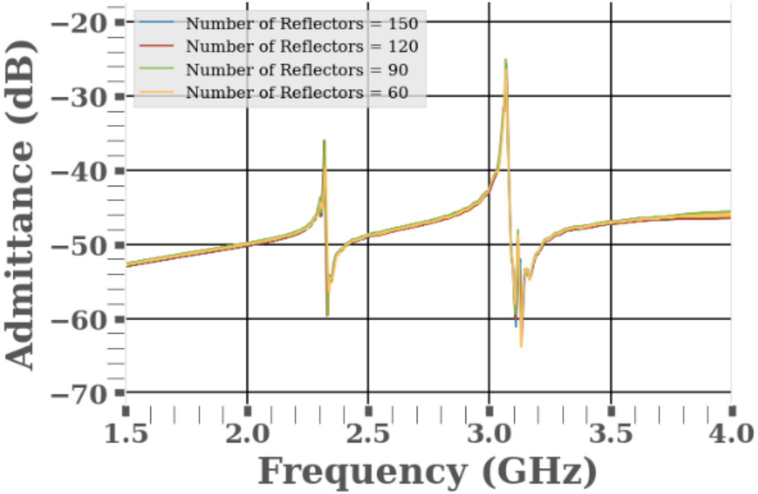


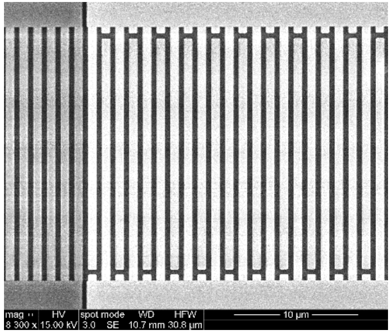


G. Esteves, T. R. Young, Z. Tang, S. Yen, T. M. Bauer, M. D. Henry, and R. H. Olsson III “$Al_{0.68}Sc_{0.32}N$ Lamb Wave Resonators with Electromechanical Coupling Coefficients near 10.28%,” *Applied Physics Letters*, 118 (17), 171902, April 2021.

AlScN Surface Acoustic Wave Devices







- AlScN SAW does not require etching of the piezo material
- k_t^2 = 5.8%
- Q is 600

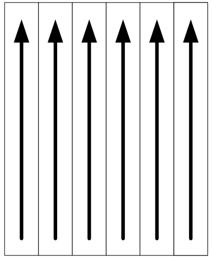
X. Du, Z. Tang, C. Leblanc, D. Jariwala and R. H. Olsson III, "High-Performance SAW Resonators at 3 GHz Using AlScN on a 4H-SiC Substrate," *IEEE Frequency Control Symposium*, Accepted

Device Performance, Applications, and Etching Requirements

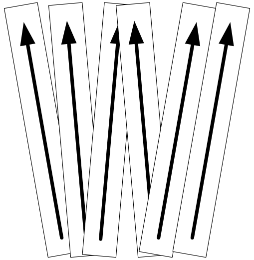
Device Type	Applications	Frequency Range	k_t^2	Q	Etching Requirements
BAW	• RF filters • Oscillators	2-6 GHz	23%	600 - 1100	• Thickness of 300 – 1000 nm • Does not require vertical sidewall • Stop on bottom electrode material
MEMS	• Oscillators • Sensors • Energy harvesting • RF and IF filters	kHz to GHz	10%	1000 - 1500	• Thickness of 300 – 2000 nm • Requires vertical sidewall at high frequency • Stop on bottom electrode material
SAW	• RF filters	1 – 5 GHz	5.8%	600	• No etching
Ferroelectric	• Memory • Nonlinear photonics • RF devices	-	-	-	• Thickness 5 – 500 nm • Memory requires 100 nm diameter features in thin (~5 nm) films • Photonics requires well controlled, smooth sidewall, vertical preferred

Critical Metrics for AlScN Materials

Dipole Alignment



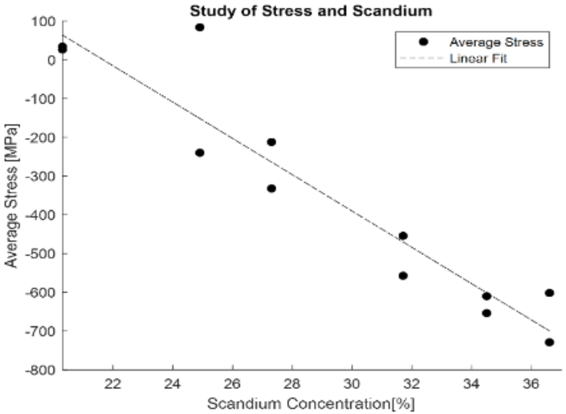
Ideal



Reality

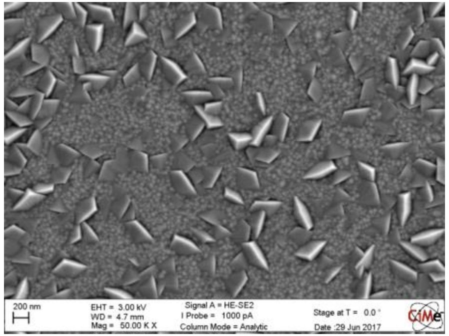
XRD FWHM is measure of film quality

Stress



Higher Sc alloying AlScN exhibits large compressive stress

Anomalously Oriented Grain (AOG) Growth

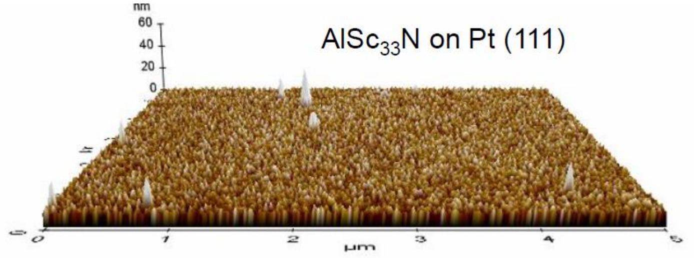


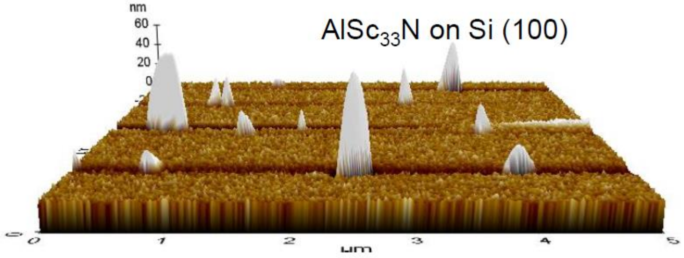
Low AOG density is key for high k_{eff}^2, low roughness, and high Q

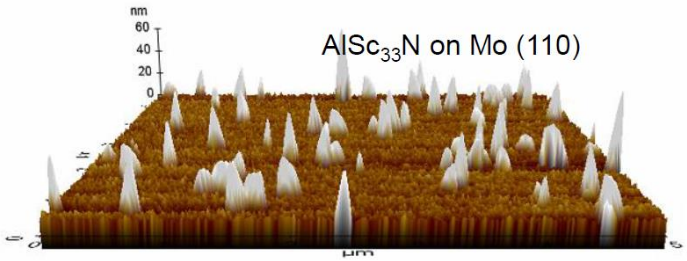
P. Muralt, “Doped AlN: Materials and Devices,” IFCS Tutorial 2019

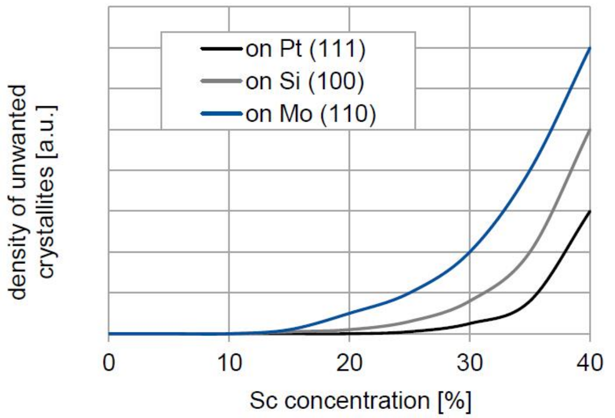
Secondary Grain Growth in AlScN

B. Heinz, “The growth of piezoelectric Al(1-x)ScxN thin films on Si (100) and Pt (111) using co-sputtering and compound target sputtering,” IEEE NEMS, April 2018.

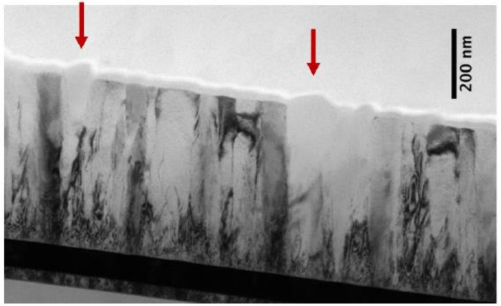




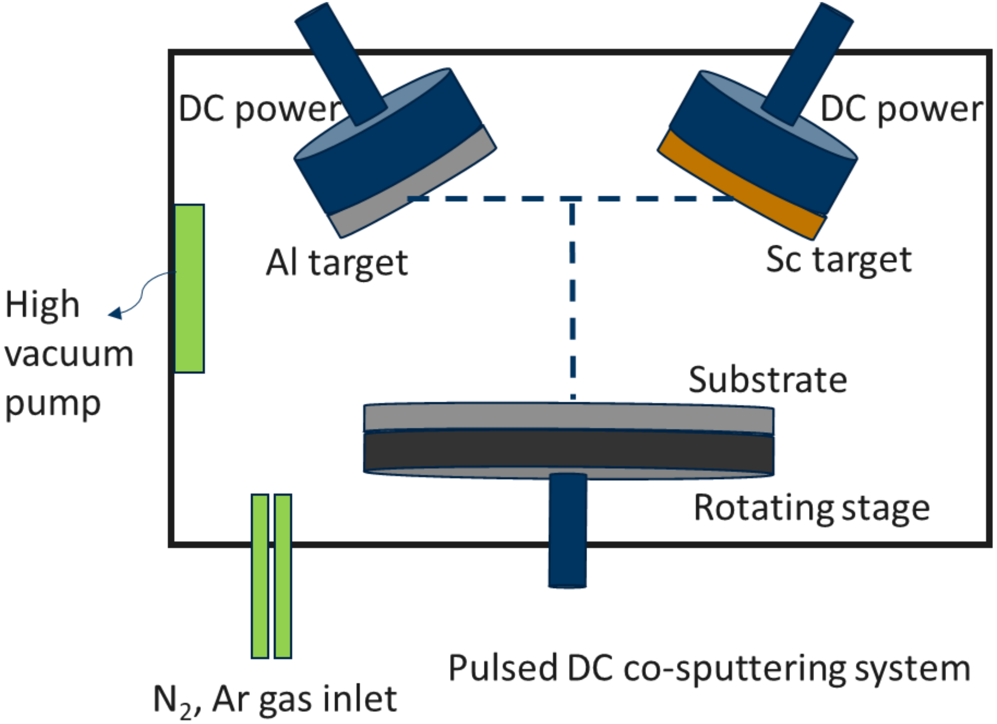




Bright field TEM picture of unwanted crystallites



AlScN Deposition Methods

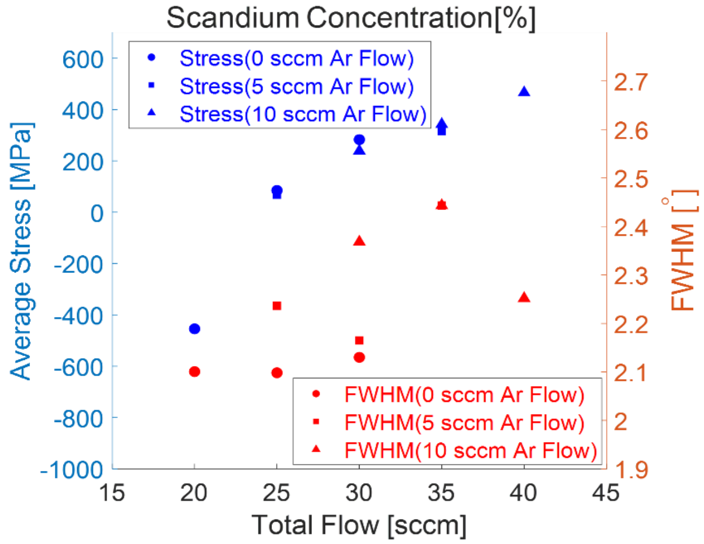


Pulsed DC co-sputtering system

Ferroelectric AlScN Growth Method

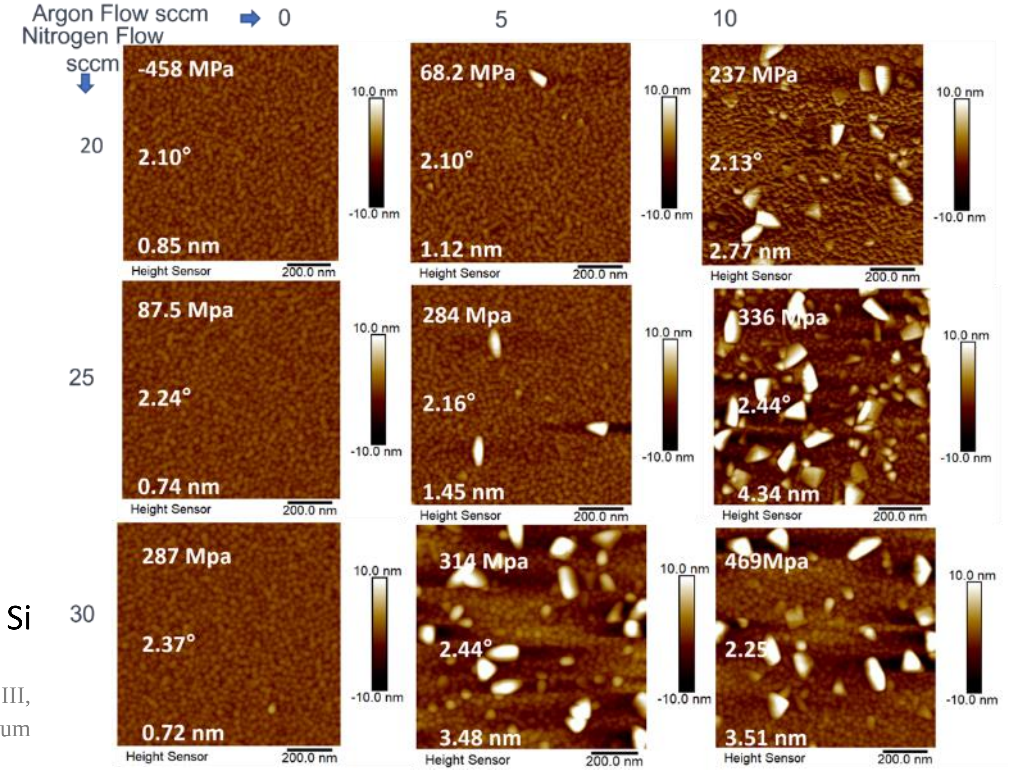
- Co-Sputtering
  - Films from 0-43% Sc
  - Deposition rate ~ 10 nm/min
  - Substrates up to 150 mm

AOG Suppression with Stress Control



Stress and crystal orientation or $Al_{68}Sc_{32}N$ deposited on Si

R. Beaucejour, V. Roebisch, A. Kochhar, C. Moe, D. Hodge and R. H. Olsson III, "Controlling Residual Stress and Suppression of Anomalous Grains in Aluminum Scandium Nitride Films Grown Directly on Silicon," *IEEE JMEMS*, Accepted



AOG growth and stress for $Al_{68}Sc_{32}N$ deposited on Si

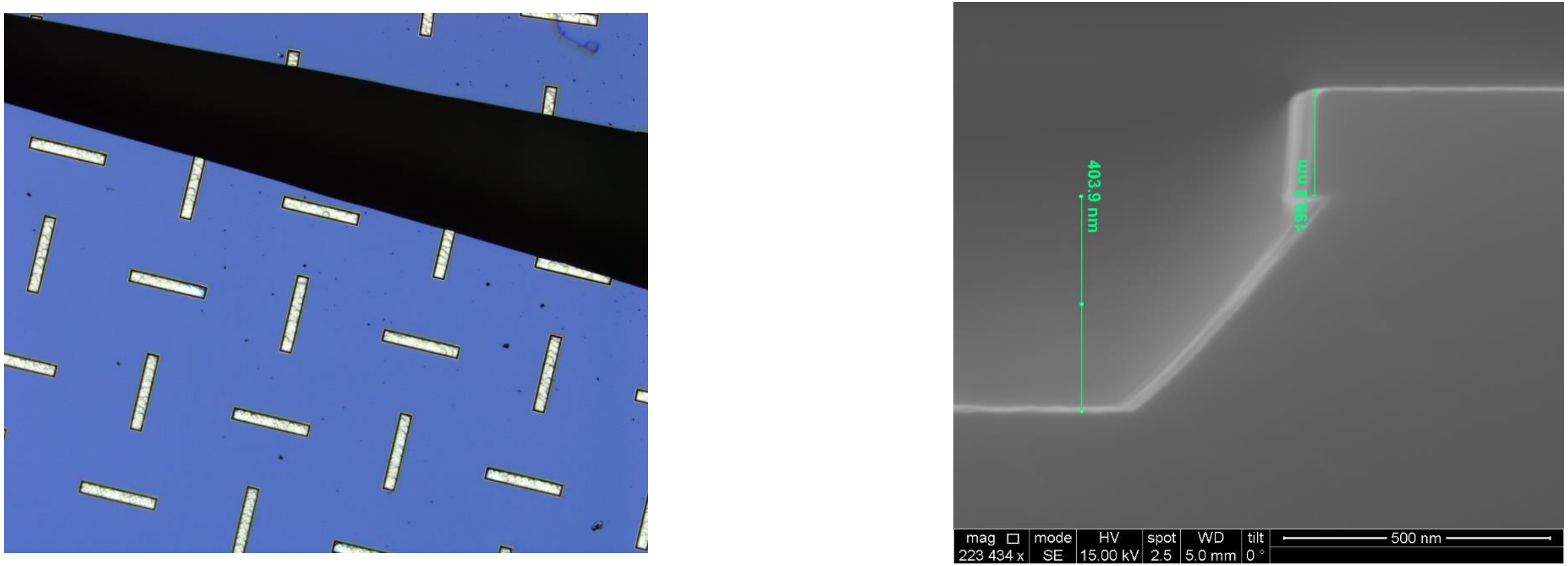
AlScN Etching Techniques

Etch Type	Etch Chemistry	Materials with High Selectivity	Notes
Dry	Cl/BCl_3, Ar Ion Mill	None	• Sidewall of 70 – 75 deg. demonstrated • Etch rate highly dependent on Sc concentration • Max. thickness of ~ 1 µm for high Sc doped materials • Requires 2-5x hard mask thickness
Wet	Hot H_3PO_4	Si, SiO_2	• Excellent when stopping AlScN etch on Si
Wet	KOH	SiN, Pt, Mo, W, SiO_2	• Excellent selectivity to SiN enables low thickness mask • Stops on a variety of metals and dielectrics • Etch rates and sidewall angles highly dependent on Sc concentration • Can form angled etches to simplify interconnect formation

AlScN KOH Etching Study

- $Al_{1-x}Sc_xN$ films were deposited on 4-inch wafers in the Evatec Clusterline 200 II tool with the range of x covering 0 to 40%;
- SiNx (200nm) film was PECVD deposited on top of the AlScN as a hard mask and on the backside of the wafer to protect the Si during the etch;
- SiN was patterned via dry etching using a CHF_3/O_2 mixture;
- A waterbath was set up via the hotplate with temperature controlled by a feedback loop;
- 300mL KOH was poured into a beaker and then put inside the waterbath to reach a certain temperature;
- The sample was then submerged in the KOH, being etched for a given time, rinsed in DI water and blow dry by N2;
- The sample is finally cleaved in the middle and cross-section imaged by Quanta 600 ESEM.

Images



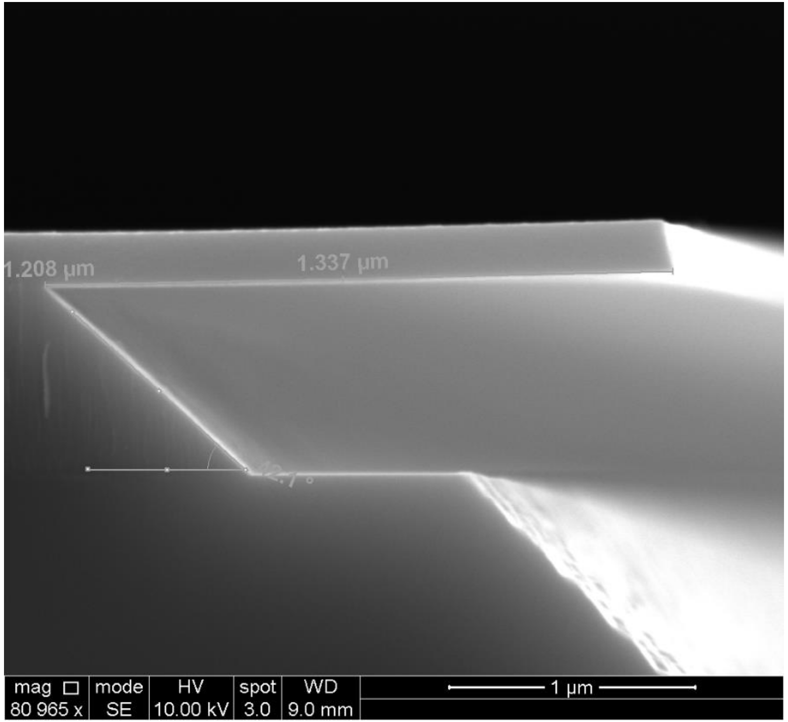
(a)

(b)

- Image showing (a) a cleaved sample after etching; (b) Cross-section SEM image of a sample etched for 30s in 30% KOH at 60^{o}C.

Z. Tang, G. Esteves, and R. H. Olsson III, “KOH Etching of AlScN Thin Films,” *Micromachines*, In-Preparation

Etch Rate Calculations

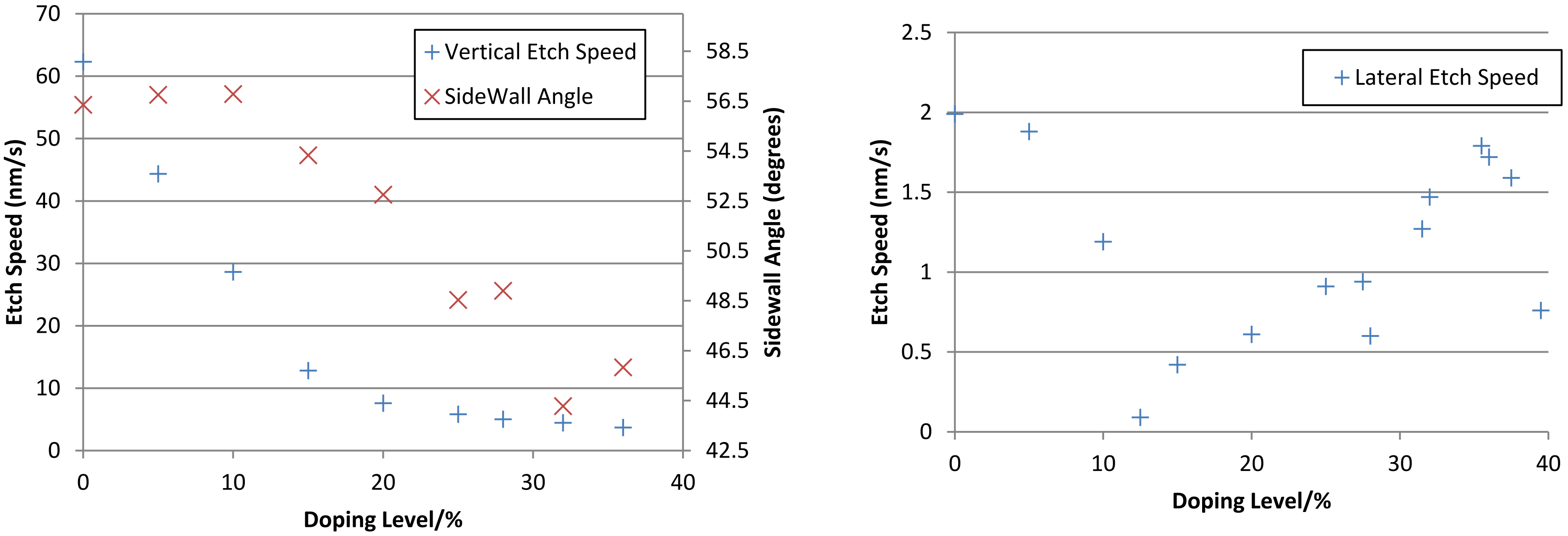


- Vertical etch rate is measured by dividing the measured etch depth by the etch time
- Lateral etch rate is measured by the undercut beneath the SiNx mask divided by the etch time
- Side wall angle is measured as shown, with 90° corresponding to a vertical sidewall

Z. Tang, G. Esteves, and R. H. Olsson III, “KOH Etching of AlScN Thin Films,” *Micromachines*, In-Preparation

Etch Rate Findings

Etch rates of AlScN vs. doping for 30% KOH @ 45 °C



- Etch rates vary substantially with Sc doping
- Etch rates vary with temperature and concentration but relative etch rates vs. doping are unchanged

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Z. Tang, G. Esteves, and R. H. Olsson III, “KOH Etching of AlScN Thin Films,” *Micromachines*, In-Preparation

Controlling the Sidewall Profile

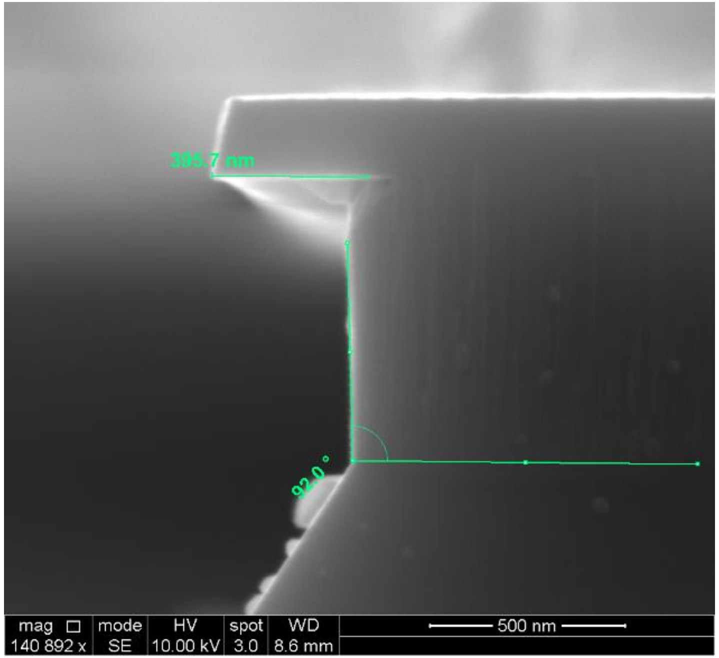

Image showing a 12.5% AlScN film etched in 10% KOH at 65°C for 20 min. A vertical sidewall is achieved.

- By balancing the vertical/lateral etch rates and etching time vertical sidewalls can be formed for some Sc concentrations

Z. Tang, G. Esteves, and R. H. Olsson III, “KOH Etching of AlScN Thin Films,” *Micromachines*, In-Preparation

Biomedical & IoT Integrated Communications and Sensing Laboratory (BIOTICS)

Doctoral Students


Baha Bachnak


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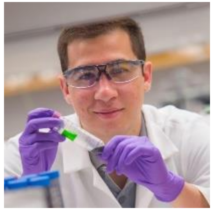
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