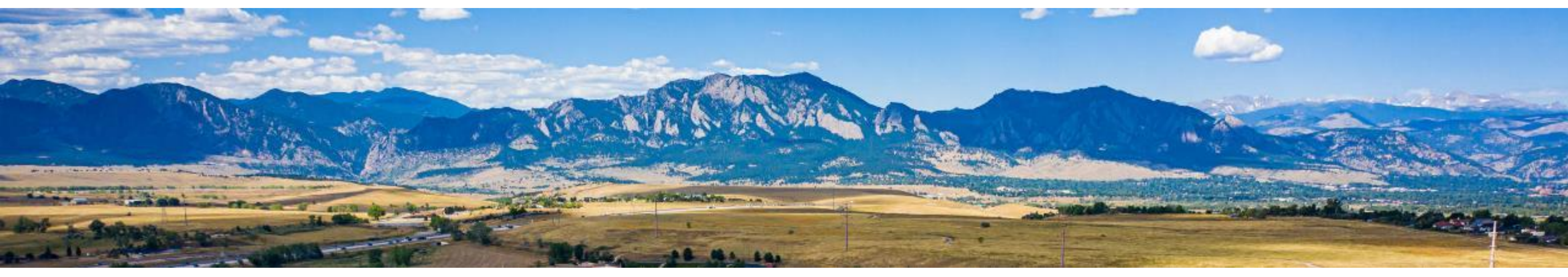
Dynamic Control of ALD Films for Fast & Efficient MEMS Manufacturing

Matt Weimer, PhD

Principal R&D Scientist

Forge Nano

We Make Materials Better



HQ outside Denver, Colorado, USA

Install base and satellite offices across Europe and Asia

World's largest particle ALD coating equipment

World's fastest and most efficient object/wafer ALD equipment

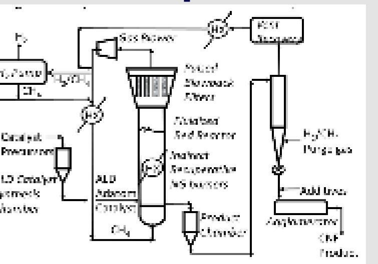
End-to-end ALD Solutions Provider

End-to-End Solutions Provider

Equipment Sales

- Portfolio of ALD coating equipment
- Powder Coating and Wafer Coating Systems
- Designed and delivered for customer application and throughput needs

Product/Process Development



- Internal facility for proof-of-concept demonstrations
- Technical support for novel process development and optimization
- Novel chemistry testing and supplier validation

Toll Coating and Licensing

- On-going agreements for production scale operations
- Continued revenue based on proprietary FN process development and expertise

Precursor Management

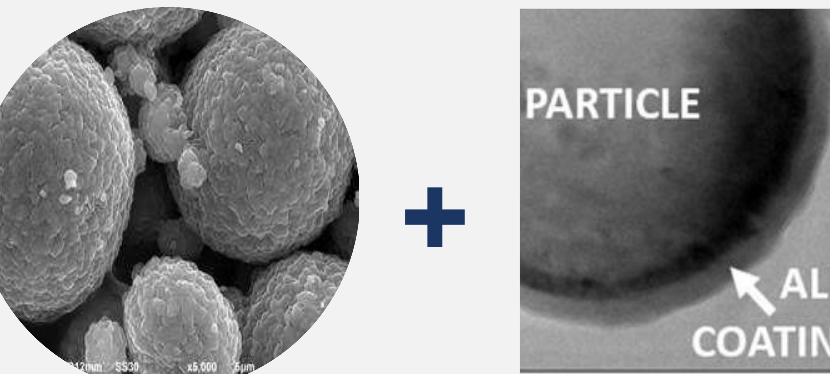
- Automated precursor level monitoring and re-order process
- Best pricing through FN sourcing
- Validated suppliers
- Range of chemistries

Maintenance Services & Spares

- Equipment uptime and performance assurance
- On-site mnt and operational-support programs
- Remote support and equipment monitoring capability

Full Equipment and Service Provider from early proof of concept through commercial production

Raw Materials



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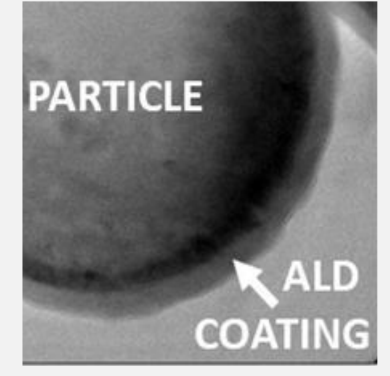
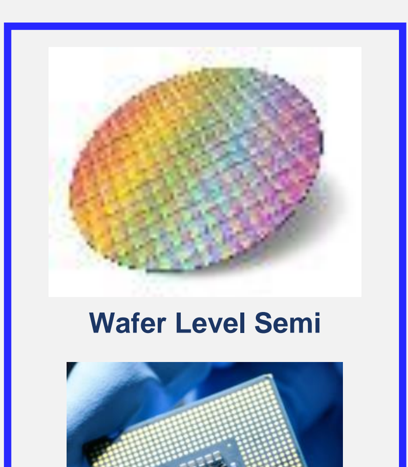
Nano Coatings



ALD
Atomic Layer Deposition

=

Better Products



Wafer Level Semi

Device Level Semi

Batteries

3D Printing

Magnetics

Catalysis

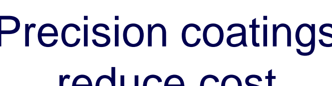
Fuel Cells

Benefits of Forge Nano coatings

Strong chemical bond to surface

Modify surfaces to enhance performance

Uniform and pin-hole free coatings



Precision coatings reduce cost

ALD used as gate dielectric in logic, word line fill in 3D NAND, passivation in MEMS/OLED, surface passivation in PERC solar

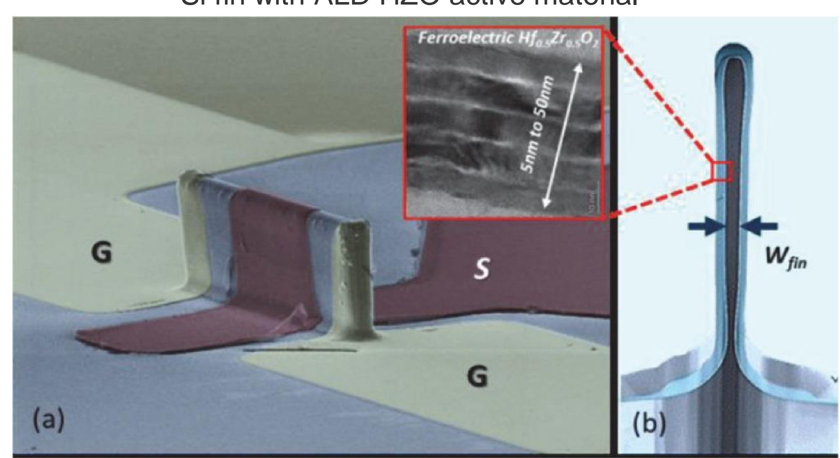
ALD provides enabling technology for current and next-gen MEMS

Functional Materials

Provide primary or ancillary function

- Physical properties modulated during operation
  - Electrical polarization
  - Internal film stress and strain
  - Index of refraction
  - Phase

Si fin with ALD HZO active material



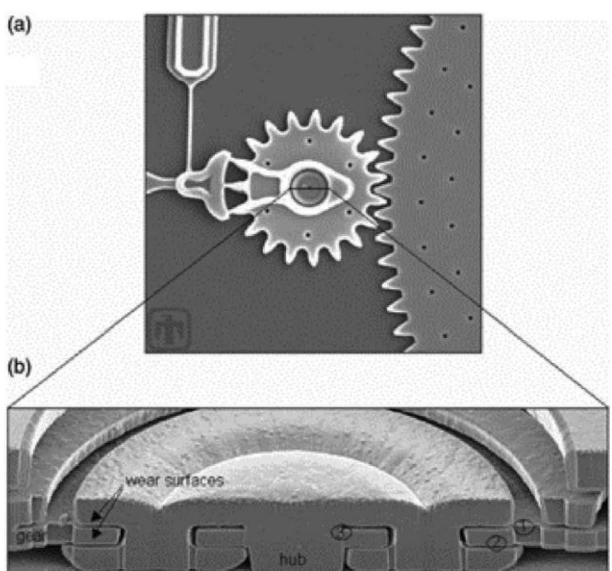
Hakim et al., IEEE Micro. Wire. Cmpnts. Lett. 31(6), 2021

Passive Materials

Physical, chemical, or electrical protection

- Properties are static in device operation
  - **Antistiction**
  - **Tribological**
  - Hard mask
  - HF protection
  - **Dielectric barrier**
  - Charge dissipation
  - **Moisture barrier**
  - Interface passivation
  - Anti-reflection
  - Support

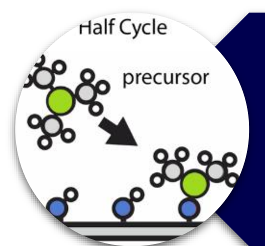
Ball bearing with 10 nm ALD Al_2O_3 passivation



Mayer et al., Appl. Phys. Lett. 82 (17), 2003

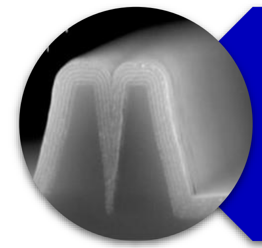
Strnad et al., J. Vac. Sci. Technol. A, 41 (5), 2023,: 050801.
https://doi.org/10.1116/6.0002431

ALD is still underutilized in current MEMS manufacturing

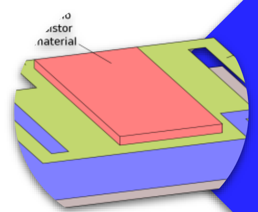


ALD Basics

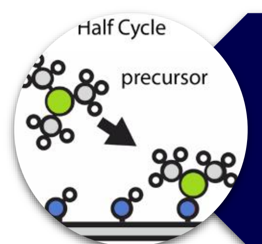
Forge Nano ALD^x Difference



Advanced Applications for ALD



ALD Applications for MEMS Devices



ALD Basics

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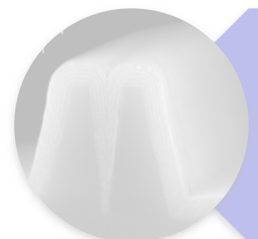

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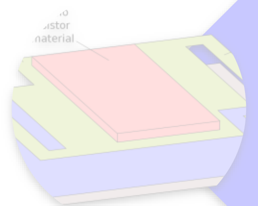
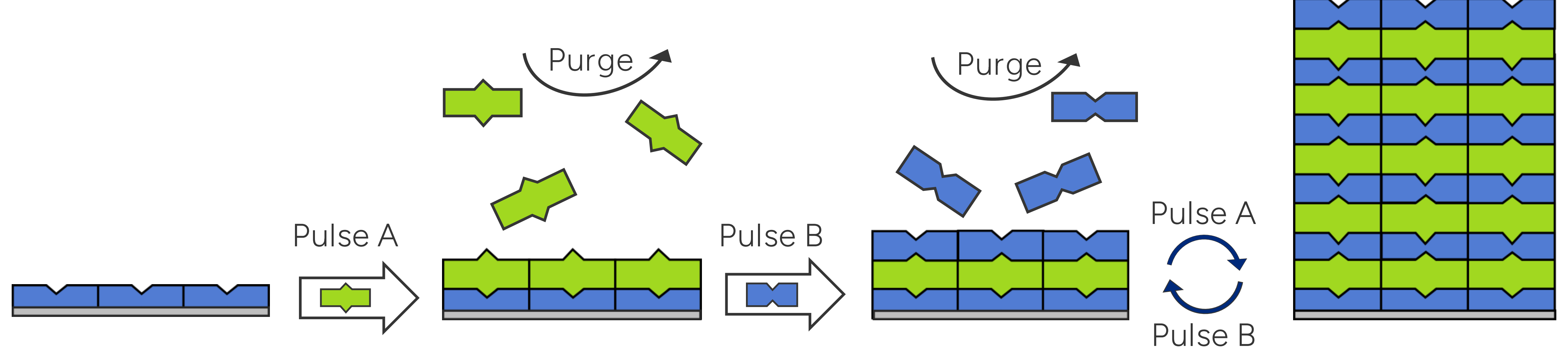


ALD Applications for MEMS Devices

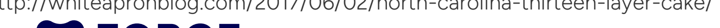
Atomic Layer Deposition – The Basics

ALD is all about sequential surface reactions to deposition thin films atomic layer by atomic layer



How can one visualize surface chemistry?

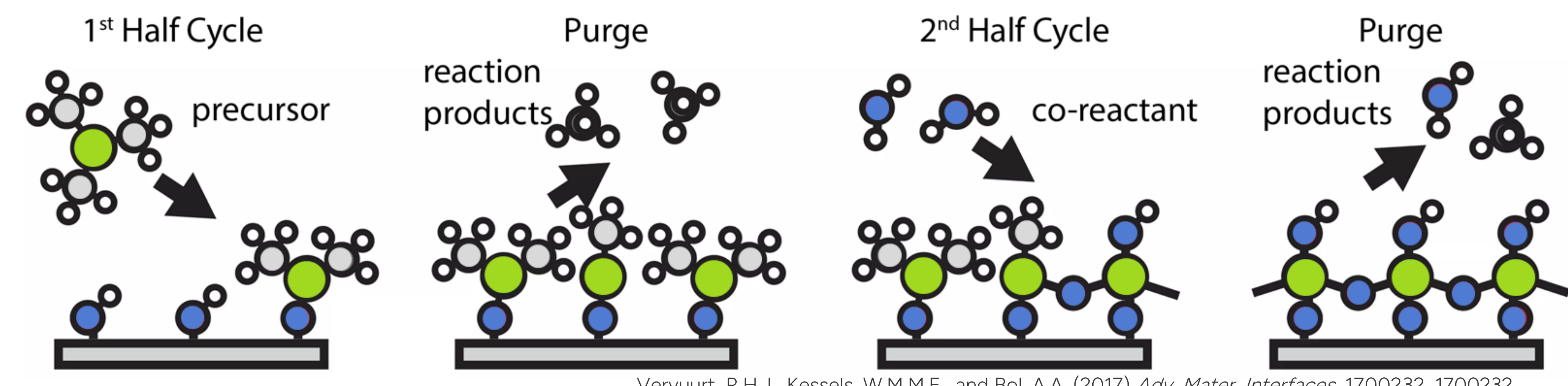
How to Visualize Atomic Scale Chemistry



Who doesn't love cake?

Atomic Layer Deposition – Chemistry

Based on spontaneous, sequential, self-limiting thermal reactions that add material with atomic level control

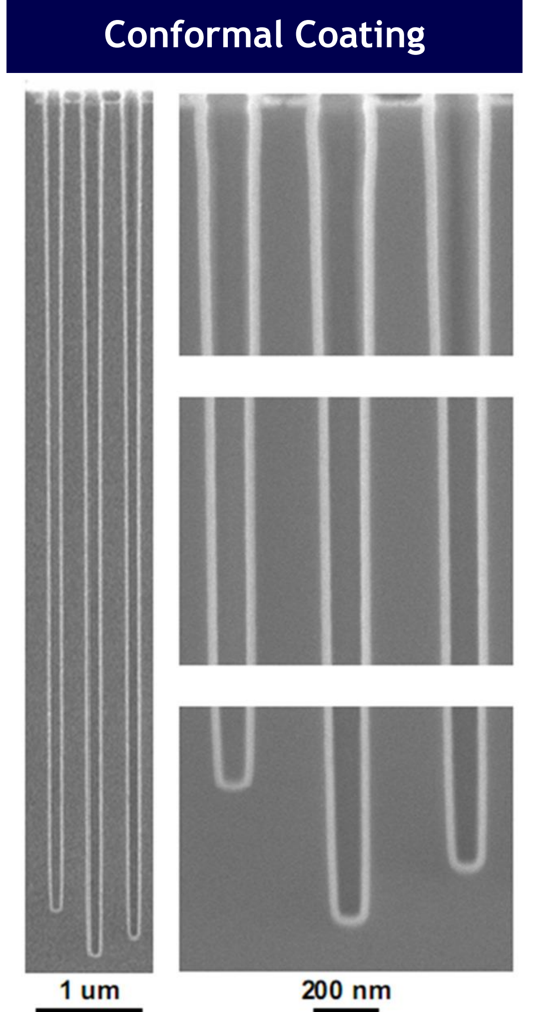


Vervuurt, R.H.J., Kessels, W.M.M.E., and Bol, A.A. (2017) *Adv. Mater. Interfaces*, 1700232, 1700232

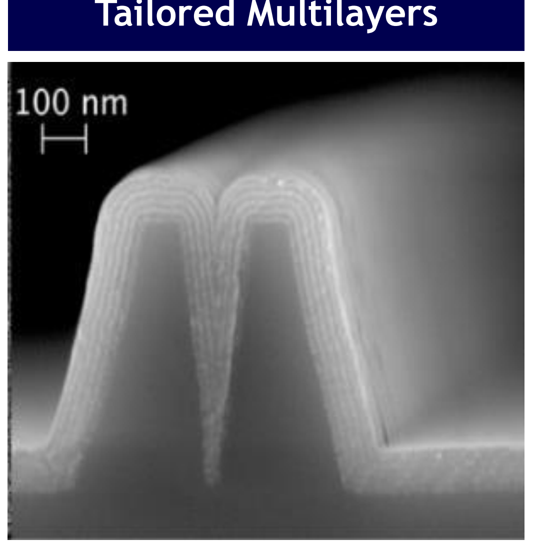
Self-limiting surface chemistry deposits conformal, uniform, pin-hole free films, with good surface adhesion

Self-Limiting Surface Chemistry Advantages

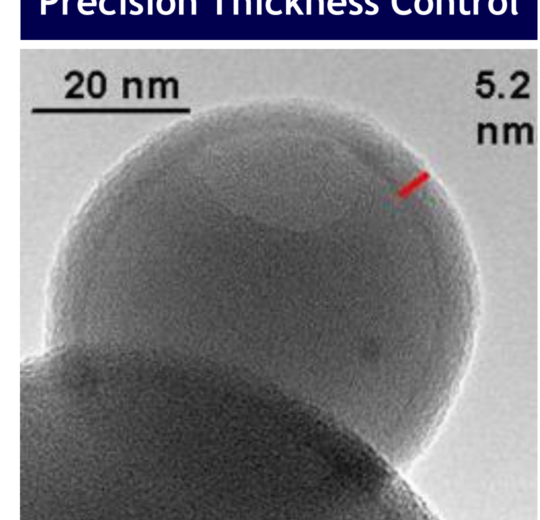
Conformal Coating



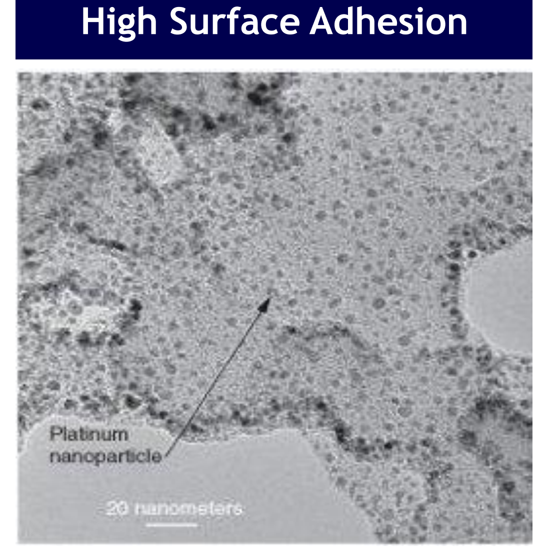
Tailored Multilayers



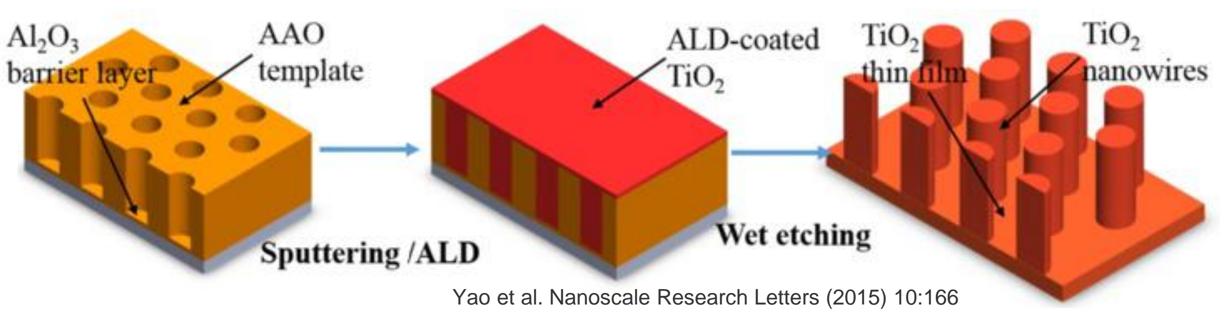
Precision Thickness Control



High Surface Adhesion



High Quality, Low Temperature Films

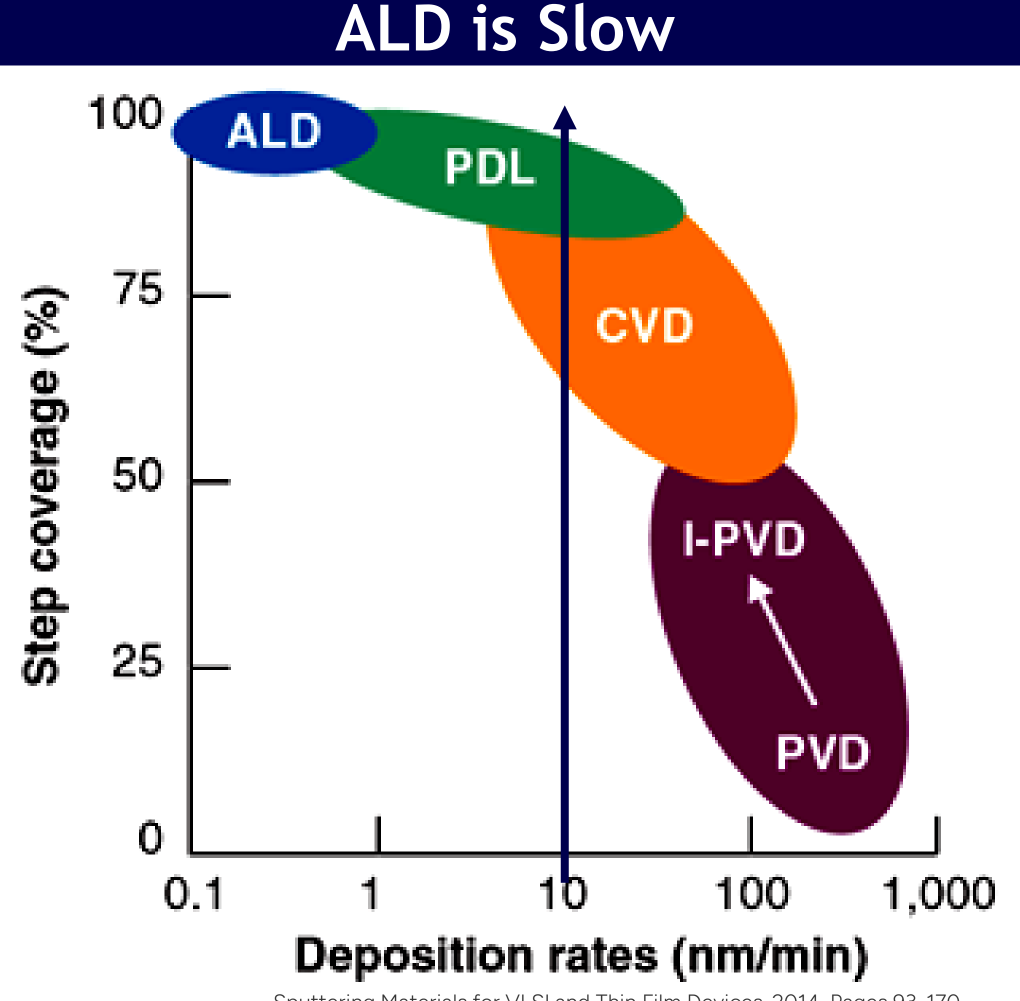


Yao et al. Nanoscale Research Letters (2015) 10:166

ALD has many applications, but it can't all be good

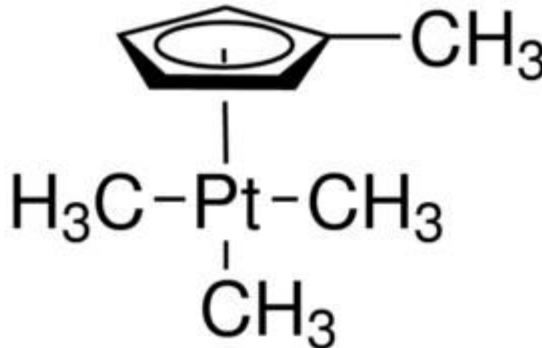
Why isn't ALD Everywhere?

ALD is Slow



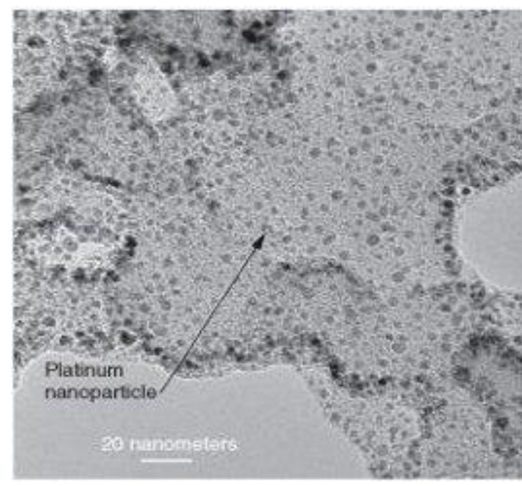
Sputtering Materials for VLSI and Thin Film Devices, 2014, Pages 93-170

ALD is Expensive



Trimethyl(methylcyclopentadienyl)platinum(IV)

\$250-450/gram → utilize ~10-20%



How can these barriers be overcome?

Precursor vs Purge Efficiency Tradeoff Barrier

Traditional ALD Reactor

Gas Flow

Cross-Flow ALD Reactor

Traditional ALD reactors are stuck in a tradeoff

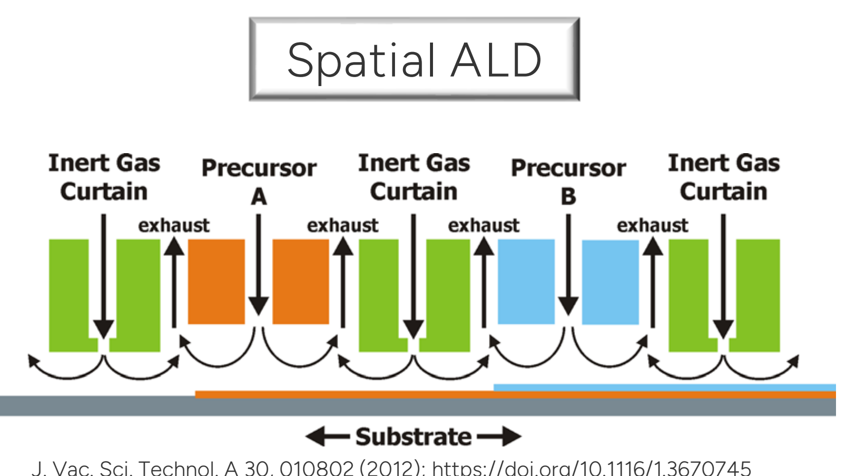
Reactor pressure **increase**	Reactor pressure **decrease**
Precursor use improves (thumbs up)	Precursor use degrades (thumbs down)
Purge time longer (thumbs down)	Purge time shorter (thumbs up)

With traditional ALD systems, one must choose between efficient precursor use or efficient purge times

How has the ALD field dealt with this tradeoff?

Cheating the ALD Tradeoff

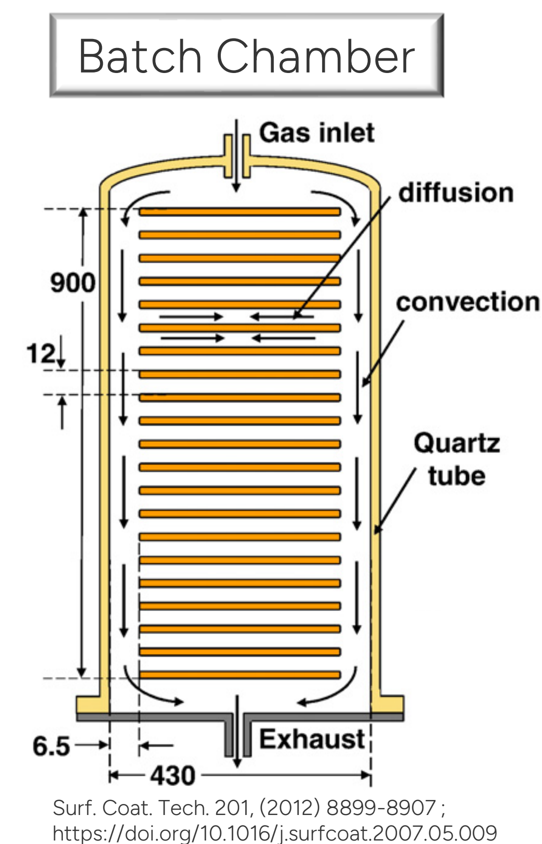
Spatial ALD



J. Vac. Sci. Technol. A 30, 010802 (2012); https://doi.org/10.1116/1.3670745

Spatial ALD		Batch ALD
Very fast	**Speed**	Very slow
Slightly better	**Precursor Consumption**	Much worse
Middling	**Thickness Uniformity**	Very uniform

Batch Chamber

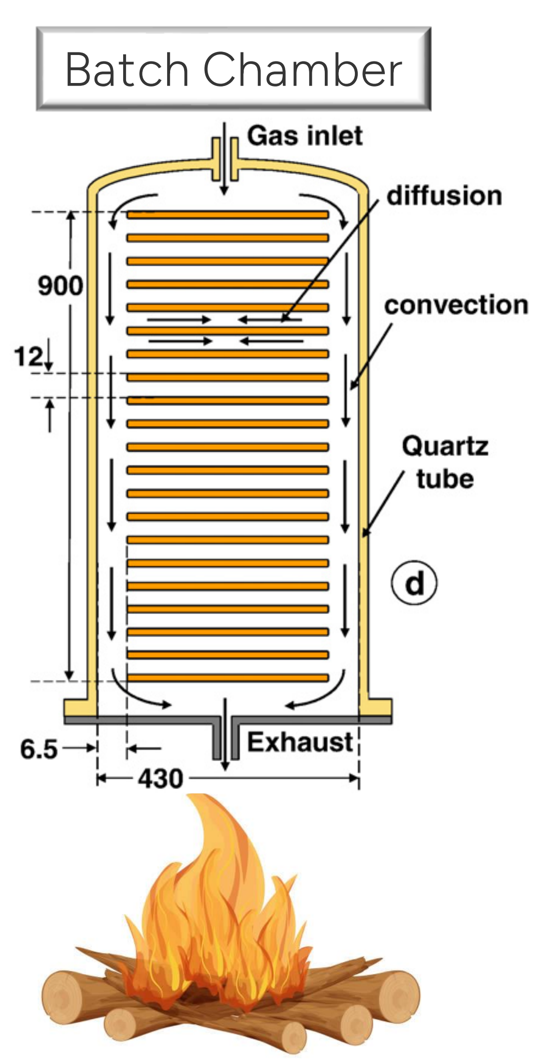


Surf. Coat. Tech. 201, (2012) 8899-8907 ; https://doi.org/10.1016/j.surfcoat.2007.05.009

Batch system have high throughput with volume, not speed

Neither addresses the main pressure/consumption tradeoff

Batch ALD Tools Can Degrade MEMS Performance



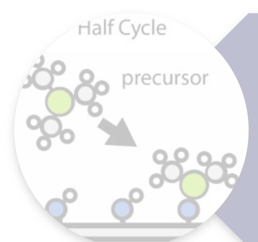
Time at temperature, not just overall temperature, matters

Batch ALD can **take days longer**, increasing the time at temperature leading to **degradation of films and properties**

Up to **60% decrease in PZT piezoelectric coefficient** after extended time at elevated temperatures

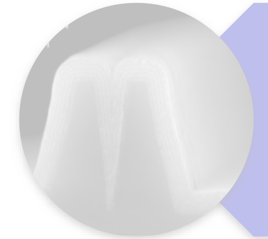
Single wafer has a **more traditional thermal budget** making it ideal for MEMS

Single wafer ALD tools are preferred, and often required, for MEMS applications

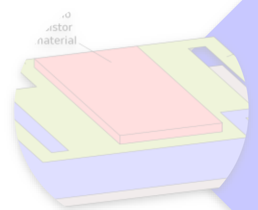


ALD Basics

Forge Nano ALD^x Difference



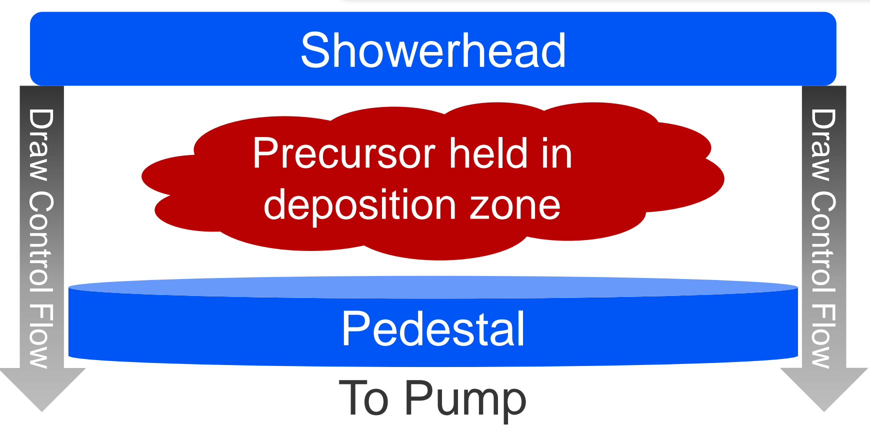
Advanced Applications for ALD



ALD Applications for MEMS Devices

ALD^x enables Dynamic Precursor Pressure Control

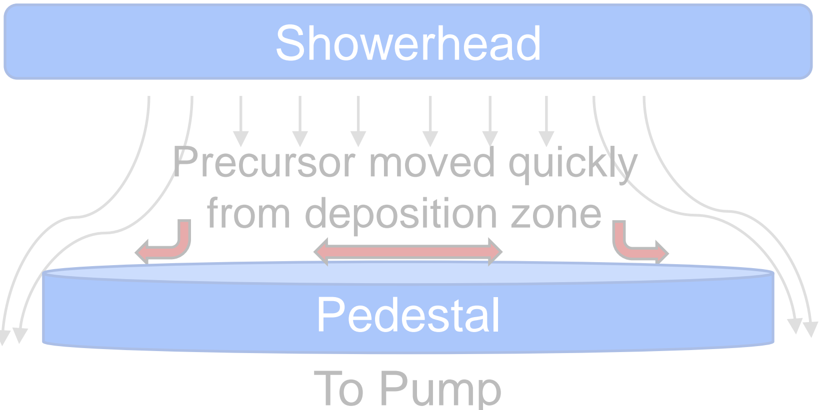
Synchronously Modulated Flow and Draw (SyMoFD)



Draw Control On

Equal to a long precursor residence time
80-90% chemical utilization

Enables up to **<u>100x less precursor use</u>**
Typical precursor exposure <50ms



Draw Control Off

Equal to a short precursor residence time

Enables short cycle time **<u><1s per cycle</u>**
Typical fast purge time <0.5s

George, S., Chem. Rev. **2010,** *110,* 111–131

SMFD lives in both pressure regimes and breaks the tradeoff

ALD^x enables Dynamic Precursor Pressure Control

Synchronously Modulated Flow and Draw (SyMFaD)

Showerhead
Draw Control Flow
Precursor held in deposition zone
Draw Control Flow
Pedestal
To Pump

Showerhead
Precursor moved quickly from deposition zone
Pedestal
To Pump

George, S., Chem. Rev. **2010**, *110*, 111–131

ALD is No Longer Slow

Step coverage (%): 100, 75, 50, 25, 0
ALD
PDL
CVD
I-PVD
PVD
Deposition rates (nm/min): 0.1, 1, 10, 100, 1,000

Sputtering Materials for VLSI and Thin Film Devices, 2014, Pages 93-170

True ALD at > 12nm/min with efficient precursor utilization

Fast Pneumatic Valves (FPV) Enable the SMFD

Precursor Cylinder

PFV Pressure Controller

Flow dictated by Pressure

FPV ALD Dose Controller

< 3 ms actuation

To Reactor

- **Made in-house FPVs enable fast cycling and efficient precursor consumption**
- **High temperature pressure control up to 200˚C**
- **High temperature chemistries are possible with FPVs**

Robust valving shorten purges and enhance consumption efficiency

Forge Nano ALD^{x} Systems and Benefits

NEW Design Coming in 2024 with Cluster Options!!

Production System for High Volume Wafer-Based MFG

Newly Redesigned

R&D System with Manual Load and Process Flexibility

Large Chamber System for boards and parts

Benefits

Fastest Cycle Times

Deposition rate up to
12nm/min
Short purge times

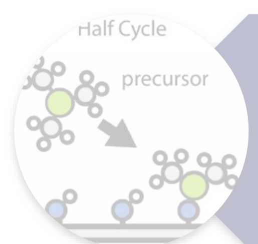
Most Efficient Precursor Use

Consumption rates up to
100x less
Short dose times

Superior Film Properties

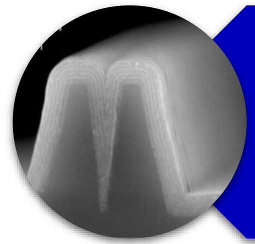
SiO_2 and HfO_2 film density
6-35% higher
Enable better films at lower °C

Proprietary technology at Forge Nano, fastest and most efficient single wafer ALD

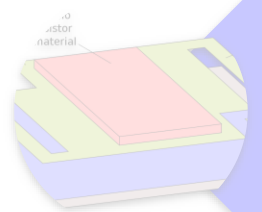


ALD Basics

Forge Nano ALD^{x} Difference

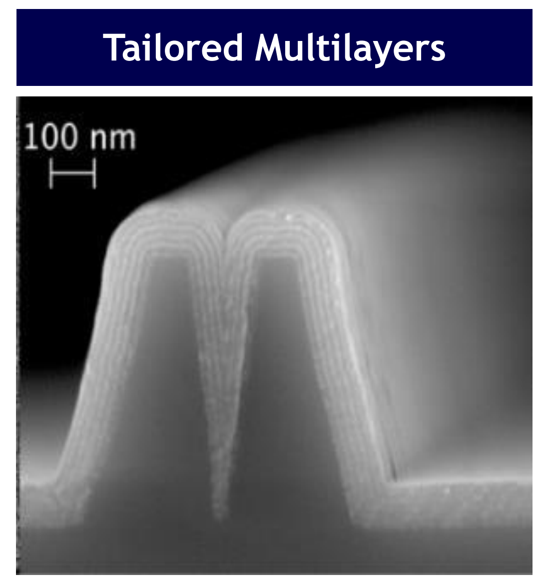


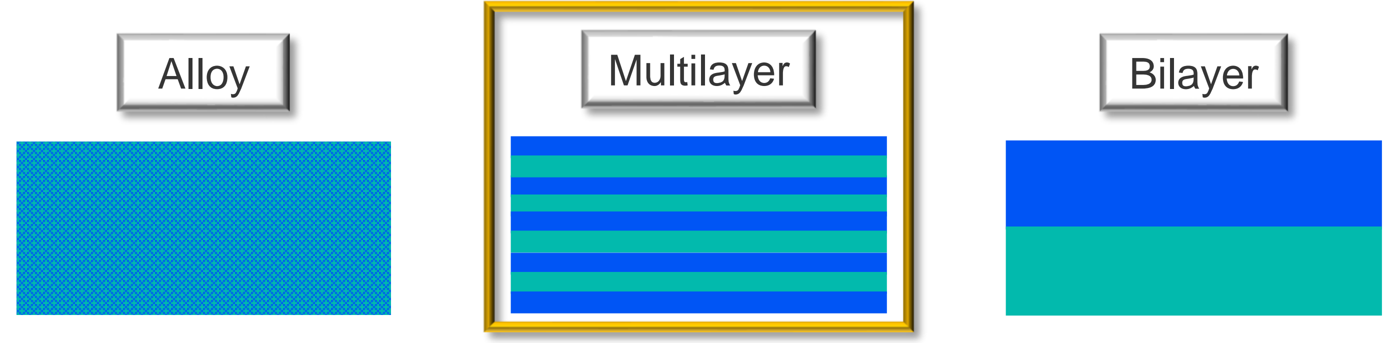
Advanced Applications for ALD



ALD Applications for MEMS Devices

Tailored Multilayers are accessible using ALD





ALD provides discrete and digital film growth with each cycle enabling layer stacks of multiple discrete materials.

Films with different properties can be layered to "tune" the bulk multilayer film properties and access:

Improved gas diffusion properties
Tunable dielectric behavior
Modified film stress

What are some examples of multilayer films?

Multilayer films via ALD enable superior moisture diffusion barrier performance in FET devices

HAST Performance

Coating	Thickness (nm)	96 hours	384 hours
PECVD	>800	Fail	Fail
ALD-CAP®	10	Pass	Fail
ALD-CAP®	20	Pass	Pass

JEDEC JESD22-A118 = HAST - 130°C/85% relative humidity
96 hrs 130°C/85% = 1000 hrs 85°C/85%

ALD used to protect RF MMIC device in harsh environments

Smaller device pitch requires conformal film

PECVD failed every test

ALD-CAP® is our ALD^x Multilayer of Al_2O_3 and SiO_2

O_2 Permeability @ atm = <$1x10^{-3}$ cm^3/m^2·day

Water vapor transport @ 38°C = <$4x10^{-6}$ g/m^2·day

Single Al_2O_3 layer was ~$1x10^{-4}$ g/m^2·day

Final solution was 50 nm ALD-CAP®

~7-minute deposition time total

Moisture barrier performance is paramount in piezo-based MEMS devices

ALD^x SiO_2 Outperforms Plasma Enhanced ALD SiO_2

SiO_2 ALD at 250°C

ALD^x SiO_2 CRISP

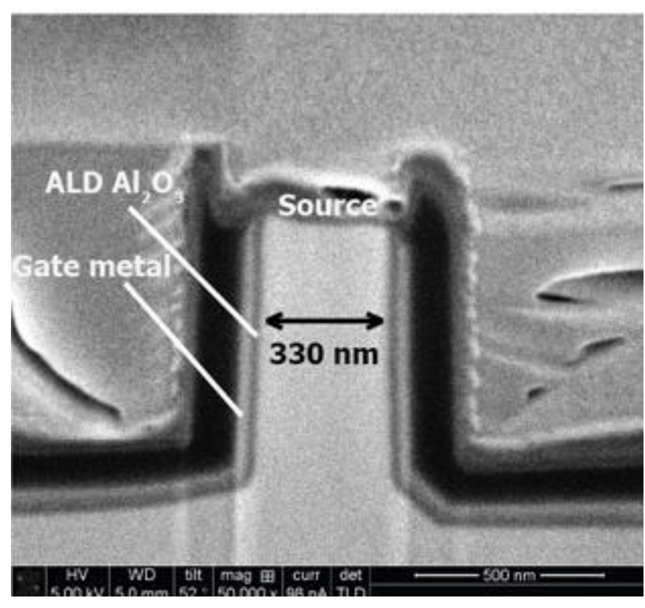
- Shorter cycle time
  - **Higher throughput**
- Lower precursor consumption
  - **Lower COO**
- Higher density, ideal stoichiometry, no impurities, better dielectric properties
  - **Better film performance in device**
- Wide temperature window
  - 75-300°C
- Ideal RI for optical applications
- No damage to substrate/stack from plasma

SiO_2	ALD^x	PEALD (BTBAS)	Forge Nano Difference
GPC (Å/cy)	1.4	1.1	**9% faster**
100 nm (hours)	0.6	2.1	**3.5x shorter**
Si Consumption per 100nm (Torr·s)	275	18,175	**66x less**
Thickness non-uniformity (6" full range %)	<2%	<4%	**2% more uniform**
RI (633nm)	1.44	1.45	**0.01 lower**
Density (g/cm^3)	2.32	2.19	**6% higher**
O:Si Ratio	2.0	2.1	**FN ideal**
Dielectric Constant	4.0	4.1	**0.1 lower**
Breakdown Voltage (MV/cm)	>12	>9	**33% higher**
Leakage Current @ 2MV/cm (A/mm^2)	$<10^{-10}$	$<10^{-10}$	**Same**

Proprietary SiO_2 CRISP ALD outperforms bleeding edge 300 mm PEALD tools

Multilayer films via ALD enable tunable dielectric barrier and leakage current behavior

Field Effect Transistor



ALD Film Composition	Dielectric Constant (ε)	Dielectric Breakdown Voltage (V_{db} - nFV/mm^2)	Leakage Current Density at 50V (J x 10^{-11} A/mm^2)
HfO_2	18.8	5.4	7.6
Composition 1	18.1	5.6	5.4
Composition 2	18.3	6	5.8
Composition 3	17.2	5.7	4.5

Dielectric constant, ε, dielectric breakdown voltage, V_{db}, and leakage current density, at 50 V, were measured for monoliths and different laminate compositions

Direct control over ε, V_{db} and leakage current density

One can choose what parameter to maximize

Many ALD oxide available for tuning

Al_2O_3, La_2O_3, ZrO_2, Ta_2O_3, Y_2O_3 and many others to tune

Can be used as an electrically isolating barrier in MEMS switches

Forge Nano ALD^x is Faster than Batch Tools

HfO_2 ALD at 250°C

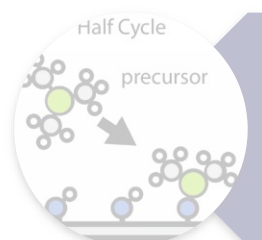
ALDx CRISP vs 25 wafer batch tool

- **>43x less time spent at temperature**
  - HfO_2 CRISP ALDx is still in R&D
  - Production tool will have a shorter cycles
- Higher wafer throughput than batch
  - Seen over multiple applications
- Lower precursor consumption
  - Saves precursor costs
  - Longer PM intervals
- Wide temperature window
  - 100-300°C

HfO_2 at 250°C	ALD^x	Batch	ALD^x Difference
GPC (Å/cy)	0.99	0.85	**18% higher**
Single cycle (s)	5.5	~200	**36x faster**
20 nm (hours)	0.3	~13	**43x shorter**
Wafers/hour	>3	<2	**~70% more**
Hf Dose (s/cycle)	0.16	~50	**312x shorter**
Hf Consumption per 20nm/**total batch** (Torr·s)		11,765	
Hf Consumption per 20nm/wafer (Torr·s)	16	470	**29x less**
Thickness non-uniformity (4” full range %)	<2%	<2%	**same**

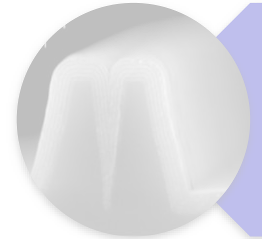
Film properties not disclosed in lit (E. Granneman et al., *Surface & Coatings Technology*, 201 (2007) 8899–8907)
Assumed a 50s Hf dose and 60s purge

Batch tools are not required for high wafer throughput ALD

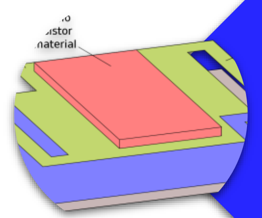


ALD Basics

Forge Nano ALD^x Difference



Advanced Applications for ALD

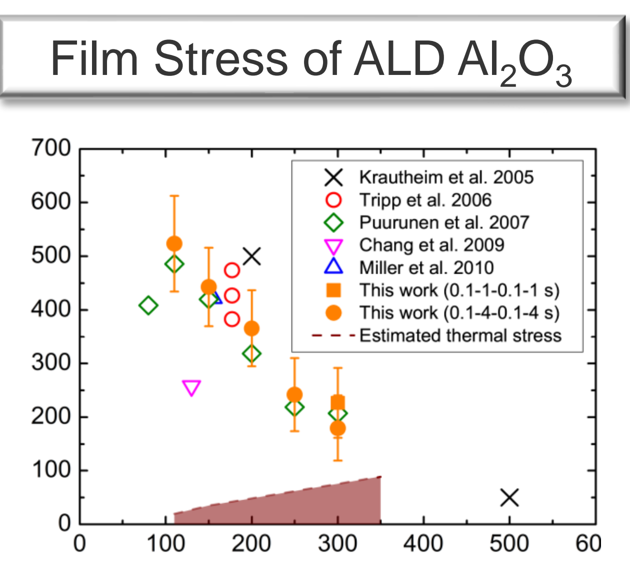


ALD Applications for MEMS Devices

Nanolaminates can modulate stress for ALD films

Different ALD processes have different stress values

Film Stress of ALD Al_2O_3

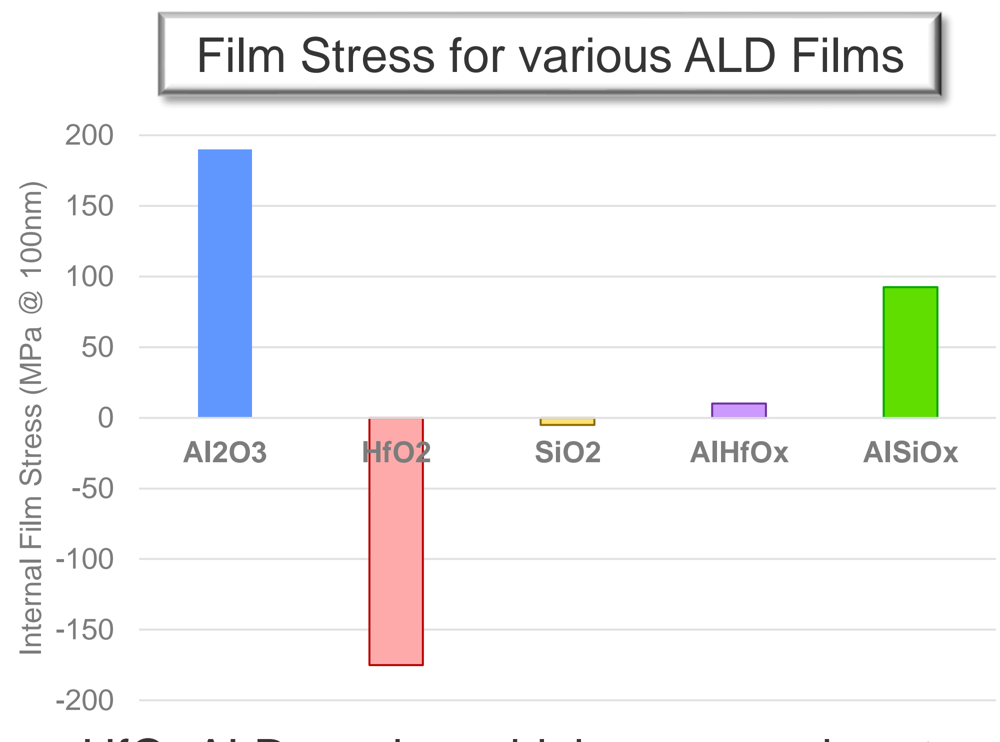


Thin Solid Films, 552, 2014, p124-135

Al_2O_3 ALD has a high tensile stress

Stress decreases with increasing deposition temperature

Film Stress for various ALD Films

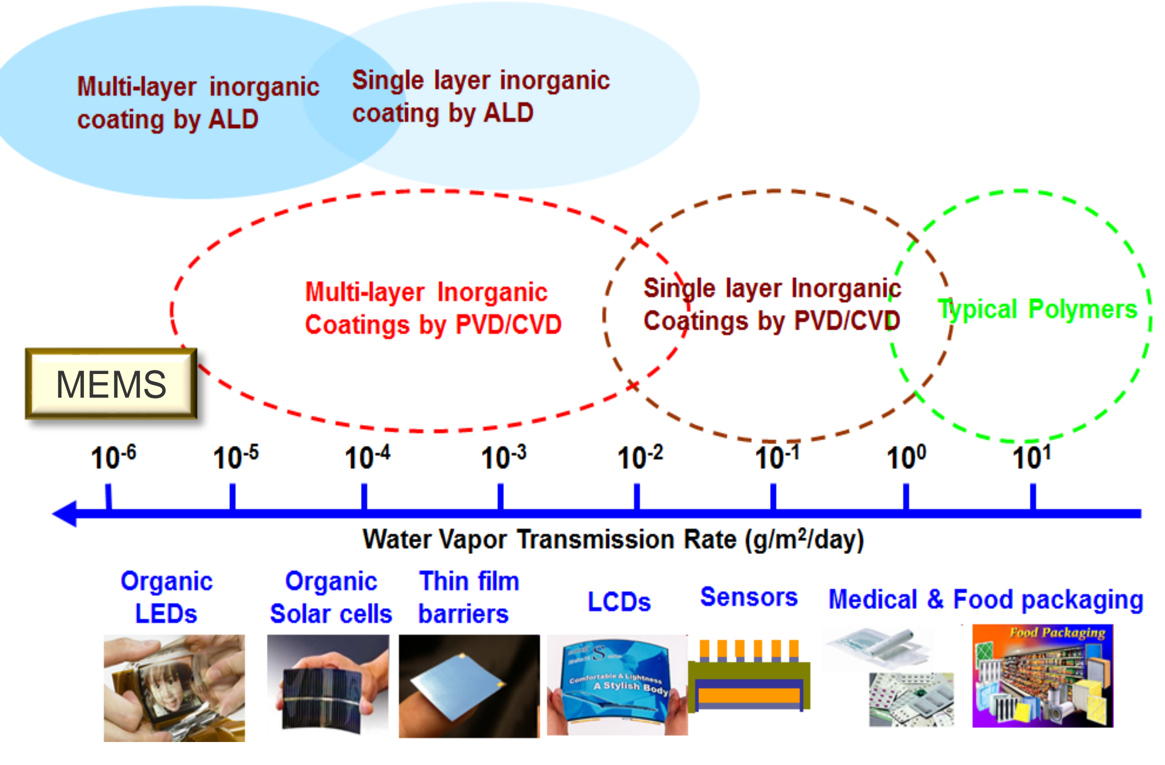


HfO_2 ALD can have high compressive stress

ALD^x SiO_2 CRISP has neutral stress

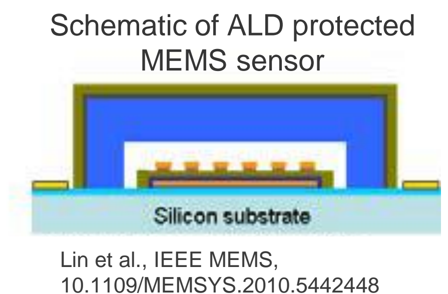
While stress can change in harsh environments**, stress tuning is critical for** actuator, microengines, Si oscillators, RF switches, cantilevers, optoelectronic and optical **MEMS, and more**

Thin, multilayer ALD films have superior moisture barrier performance suitable for MEMS technology



ALD Enabled Wafer Level Polymer Packaging for MEMS, 2011

Schematic of ALD protected MEMS sensor



Lin et al., IEEE MEMS, 10.1109/MEMSYS.2010.5442448

Multilayer ALD films have superior moisture barrier performance compared to PECVD

ALD-CAP® has water vapor transfer rate of < $4x10^{-6}$ $g/m^2 \cdot day$

Nanolaminates can modulate stress in ALD films

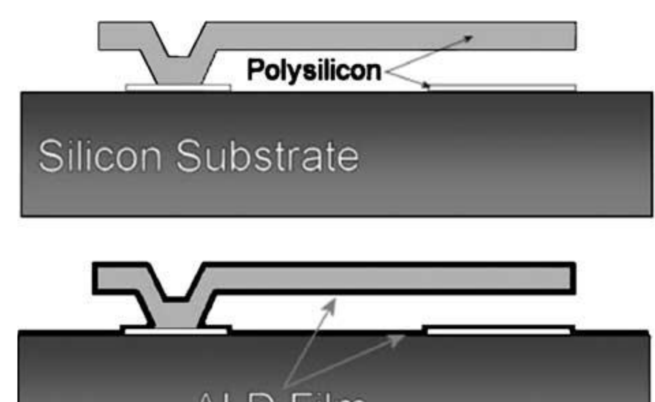
We need to know **how stress/moisture barrier properties interact?**

We are looking to partner with suitable group to study the combination of stress tuning with environmental exposure

Improving Mechanical Lifetime of MEMS with ALD

ALD offers multiple paths to improve mechanical reliability

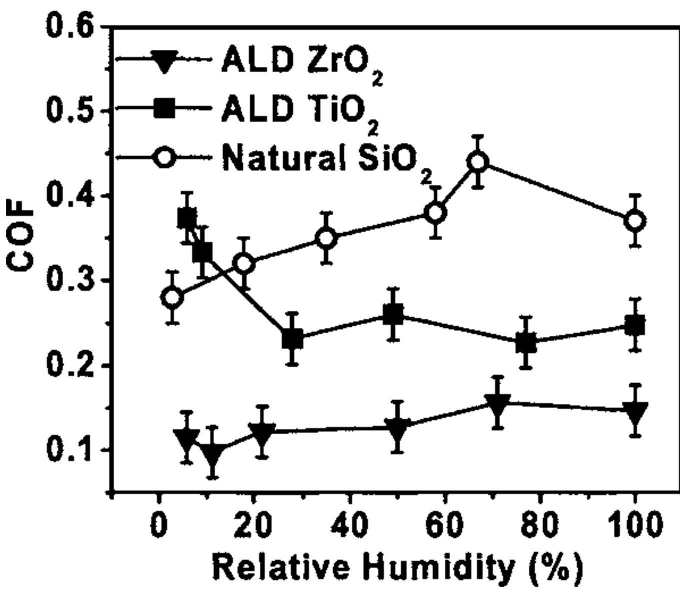
Application of **Antistiction ALD**



Hoivik et al., Sens. Act. A., 103, 2003, 100-108

Tuned with addition of hydrophobic or hydrophilic film

Increasing roughness helps
1-3 nm RMS can reduce stiction



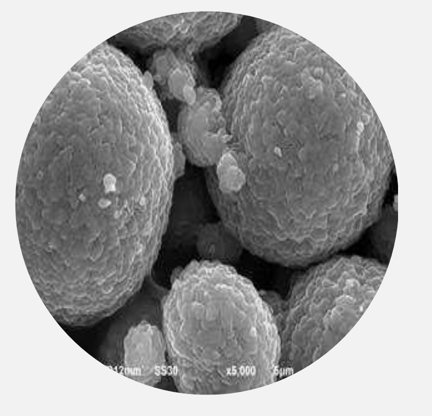
Nistorica et al., J. Vac. Sci. Technol. A 23(4), 2005

Tune coefficient of friction (COF) with different ALD films, linked to roughness

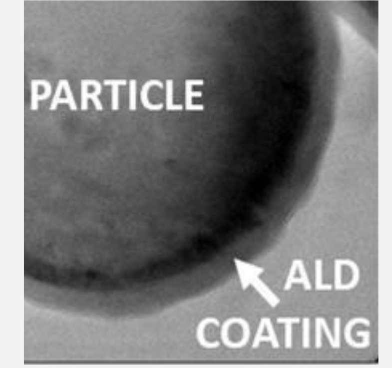
ZrO_2 lasted over 430,000 actuation cycles at 5-50 μN

Where else can ALD be exploited to improve MEMS device reliability?

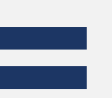
Raw Materials



Nano Coatings

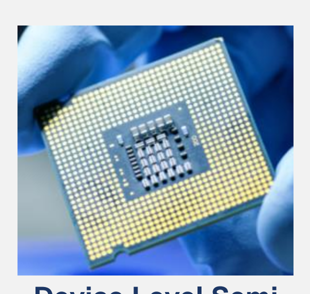


ALD
Atomic
Layer
Deposition



Better Products

Wafer Level Semi

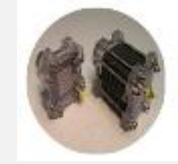


Device Level Semi

Batteries

3D Printing

Magnetics



Catalysis

Fuel Cells

Benefits of Forge Nano coatings

Strong chemical bond to surface

Modify surfaces to enhance performance

Uniform and pin-hole free coatings

Precision coatings reduce cost

ALDˣ can improve MEMS through properties modification, quickly, efficiently, and effectively

High Quality ALD Films

- CRISP process allow for development of difficult chemistries and new materials
  - Higher quality nitrides and elemental films
  - Finer control over adding dopant elements such as PO_x, SO_x, B, and N
- SyMoFD enables expensive films and precursors
  - Lower cost due to 10-100x better precursor efficiency
  - Faster cycles times by 10-100x improves throughput for slow processes
- Nanolaminates have been demonstrated for oxides, sulfides and nitrides
  - No purge delay to switch between metal precursor provides faster stack deposition

Abbreviated list of films for development

Oxides:
Al_2O_3, SiO_2, HfO_2, TiO_2, ZrO_2, Ta_2O_5, La_2O_3, Er_2O_3, SnO_2, In_2O_3, ZnO, MgO, GeO_2, Y_2O_3, VO_x, MoO_x, WO_x, MnO_x, FeO_x, CoO_x, NiO_x, CuO_x, CrO_x, CaO

Nitrides (Oxynitrides):
TiN, ZrN, AlN, TaN, HfN, VN_x, MoN_x, WN_x
MoO_xN_y, WO_xN_y, TiO_xN_y, VO_xN_y

Fluorides:
MgF_2 and YF_3

Sulfides:
ZnS, SnS_x, CuS

Dopants:
PO_x, SO_x, N, Sb, Ta, W, Nb, Li, B

Elemental Films:
Ir, Ru, Rh, Pd, Pt, Cu, Ge, W, Ni

Thank you!
Questions?

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