



# Atomic Layer Deposition: Introduction to the Theory and Cambridge Nanotech Savannah & Fiji

J Provine & Michelle Rincon

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Stanford University

NNIN ALD Roadshow

(special thanks to Ganesh Sundaram, Eric Deguns,  
Prof. H. Brongersma, and Prof. Fritz Prinz)



# Methods for Depositing Thin Films

Method	ALD	MBE	CVD	Sputter	Evapor	PLD
Thickness Uniformity	good	fair	good	good	fair	fair
Film Density	good	good	good	good	fair	good
Step Coverage	good	varies	varies	poor	poor	poor
Interface Quality	good	good	varies	poor	good	varies
Low Temp. Deposition	good	good	varies	good	good	good
Deposition Rate	fair	fair	good	good	good	good
Industrial Applicability	varies	varies	good	good	good	poor

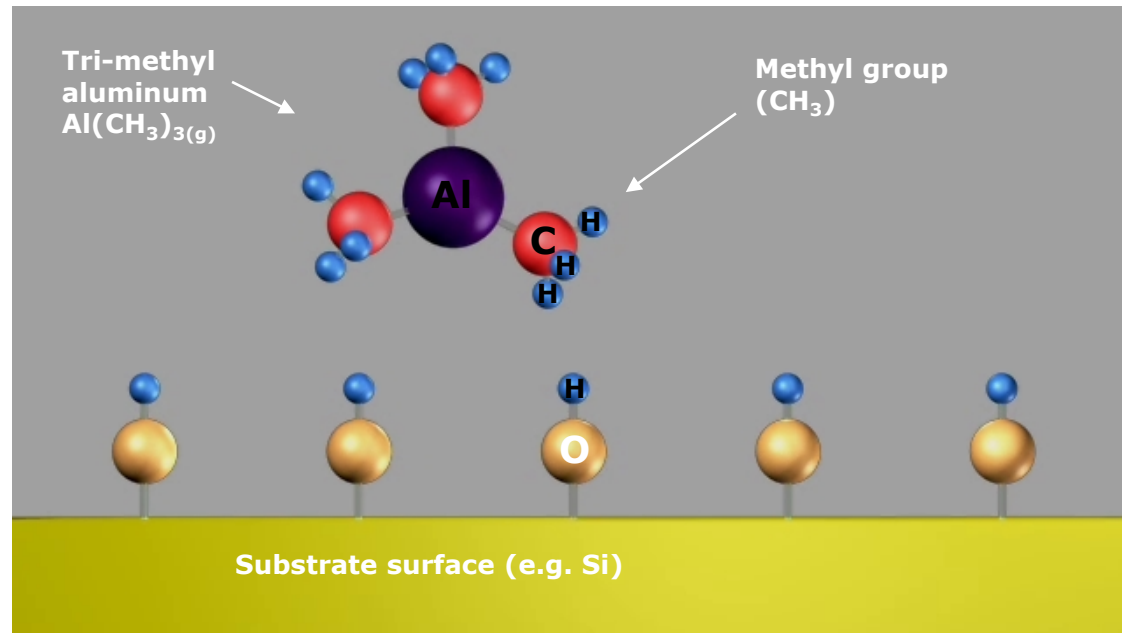


# What is ALD? aka How does it work?

- Originally called Atomic Layer Epitaxy
  - Has been around in one form or another for almost 50 years
- A chemical vapor deposition method
  - However, the reaction is split into two parts
  - Each part is self-limiting and surface only
  - After completion of the two half-reactions the system is stable and a monolayer of film has been deposited



# ALD Example Cycle for $\text{Al}_2\text{O}_3$ Deposition

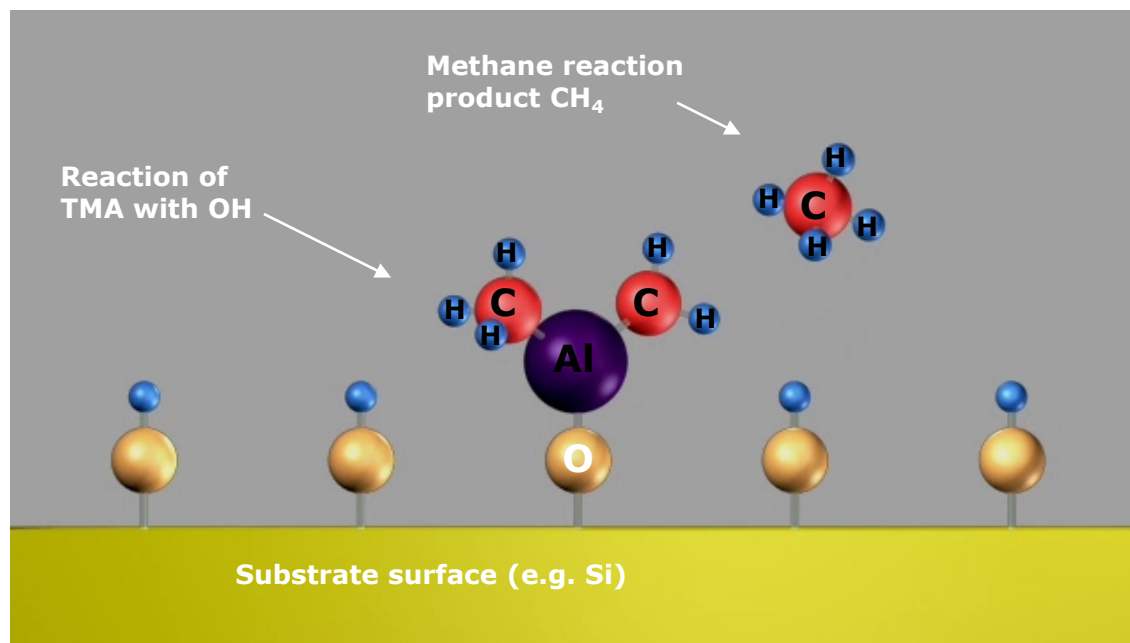


In air  $\text{H}_2\text{O}$  vapor is adsorbed on most surfaces, forming a hydroxyl group.  
With silicon this forms:  $\text{Si-O-H}_{(\text{s})}$

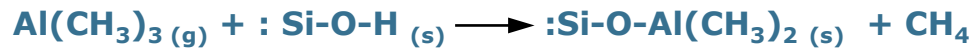
After placing the substrate in the reactor, Trimethyl Aluminum (TMA) is pulsed into the reaction chamber.



# ALD Cycle for $\text{Al}_2\text{O}_3$

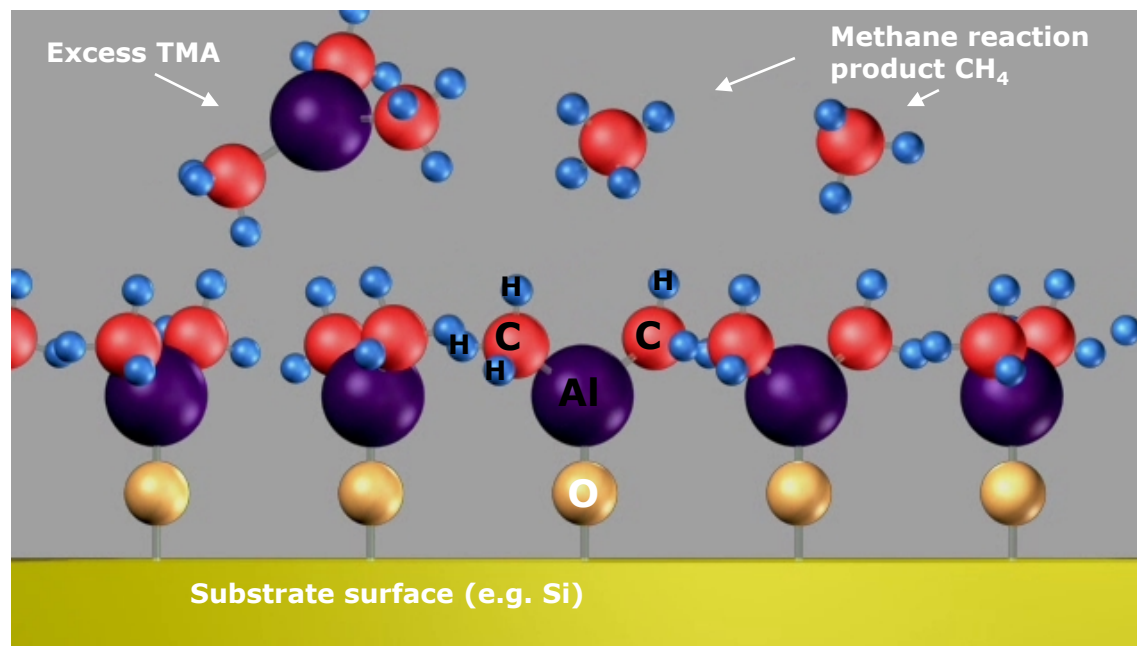


Trimethylaluminum (TMA) reacts with the adsorbed hydroxyl groups, producing methane as the reaction product





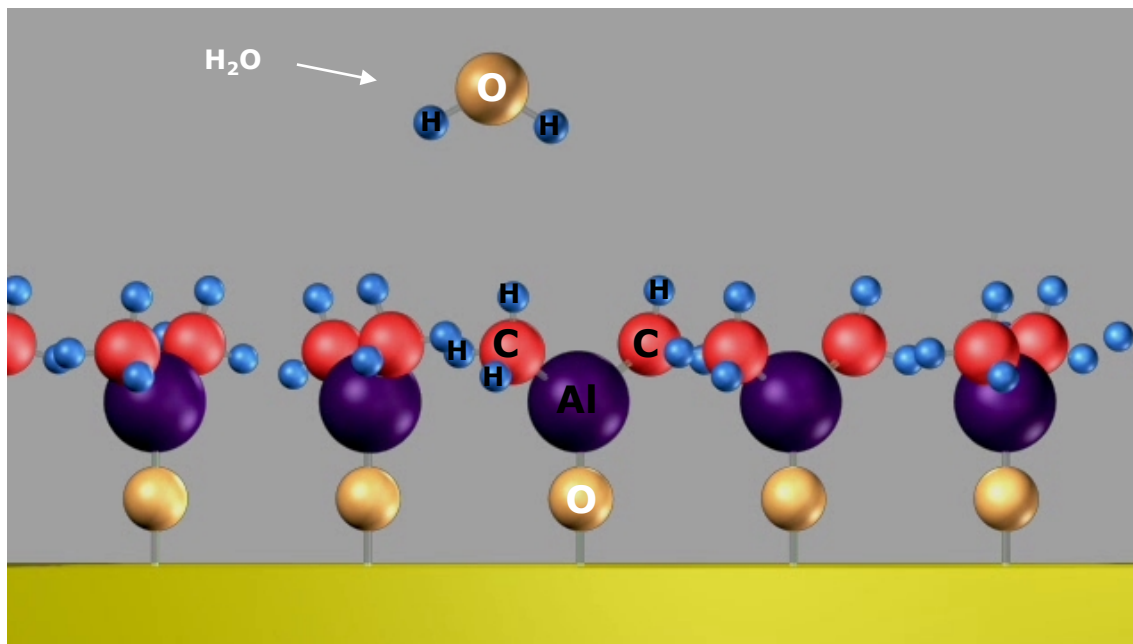
## ALD Cycle for $\text{Al}_2\text{O}_3$



Trimethyl Aluminum (TMA) reacts with the adsorbed hydroxyl groups, until the surface is passivated. TMA does not react with itself, terminating the reaction to one layer. This causes the perfect uniformity of ALD. The excess TMA is pumped away with the methane reaction product.



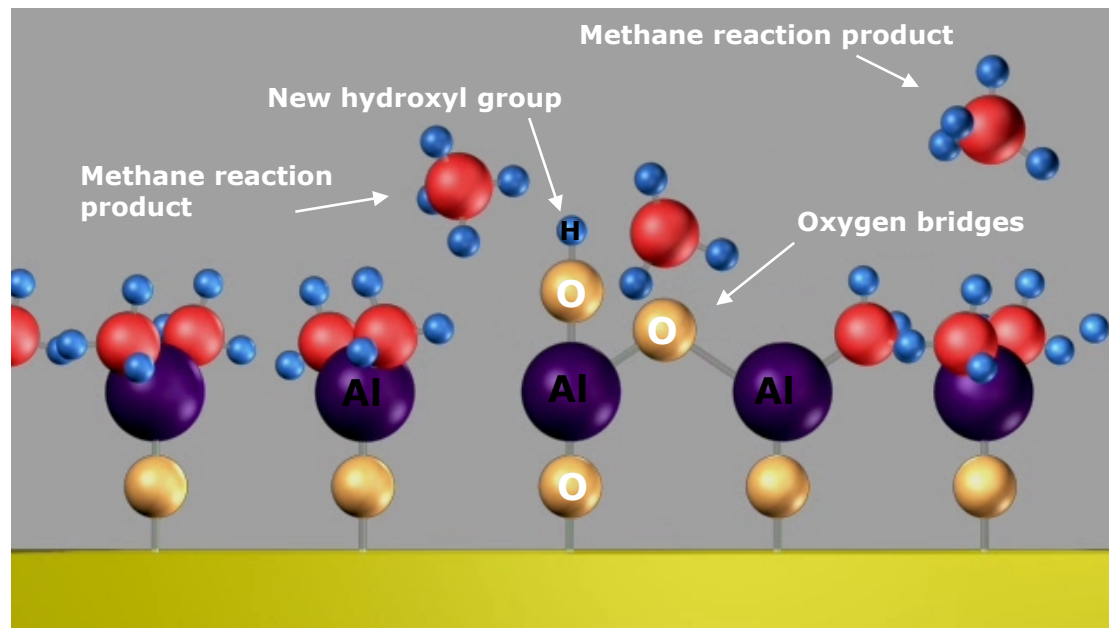
## ALD Cycle for $\text{Al}_2\text{O}_3$



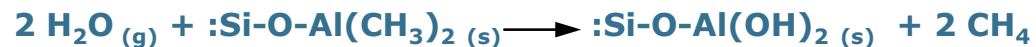
After the TMA and methane reaction product is pumped away, water vapor ( $\text{H}_2\text{O}$ ) is pulsed into the reaction chamber.



## ALD Cycle for $\text{Al}_2\text{O}_3$



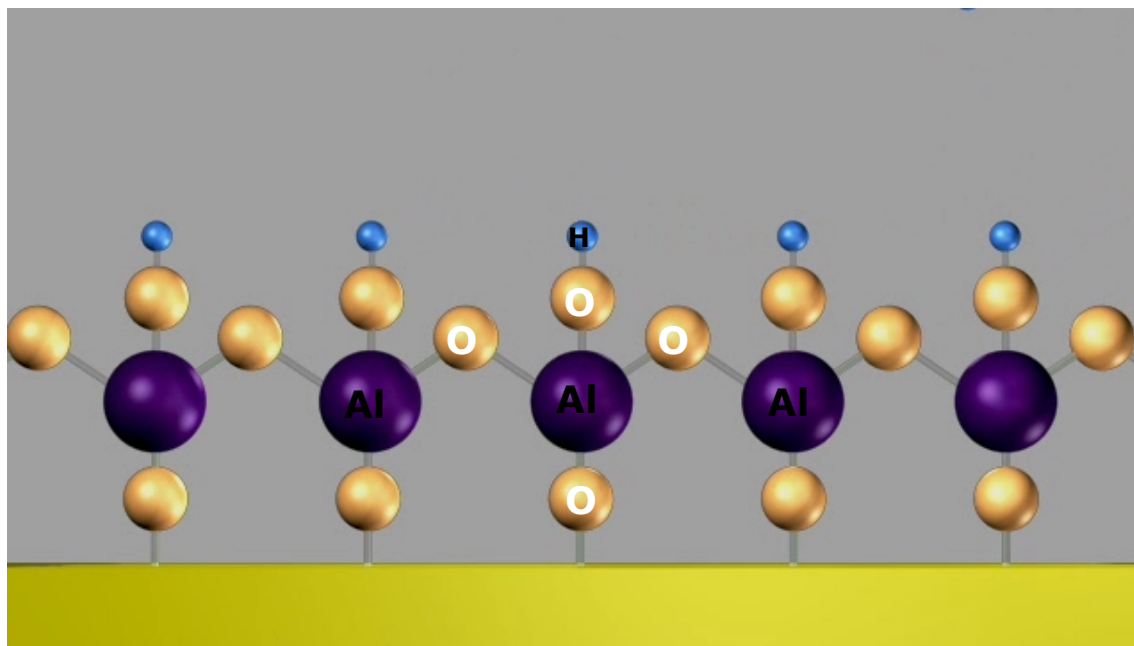
$\text{H}_2\text{O}$  reacts with the dangling methyl groups on the new surface forming aluminum-oxygen (Al-O) bridges and hydroxyl surface groups, waiting for a new TMA pulse. Again methane is the reaction product.







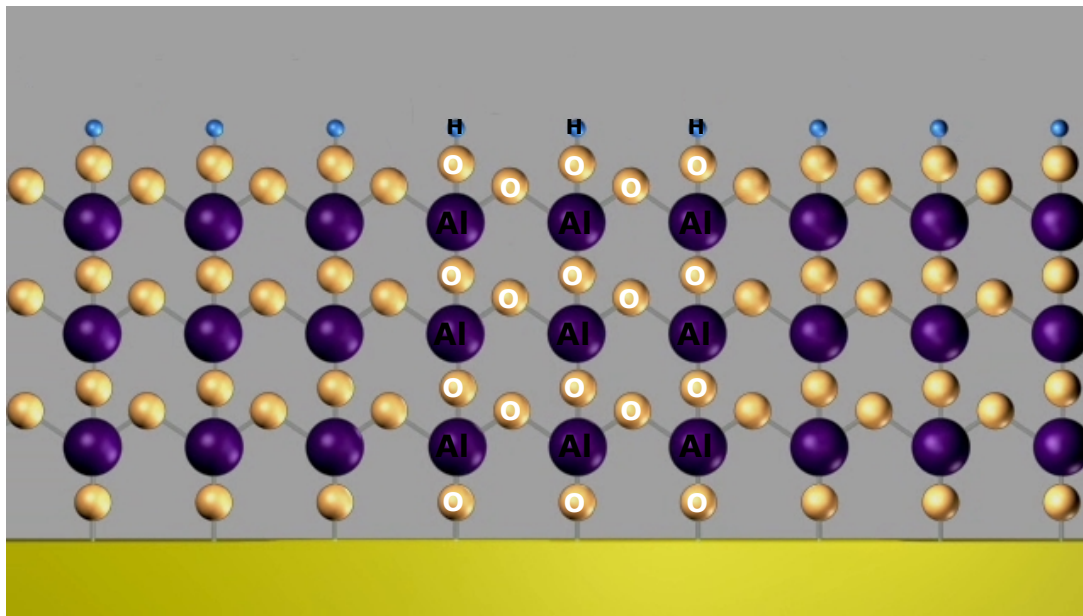
## ALD Cycle for $\text{Al}_2\text{O}_3$



The reaction product methane is pumped away. Excess  $\text{H}_2\text{O}$  vapor does not react with the hydroxyl surface groups, again causing perfect passivation to one atomic layer.

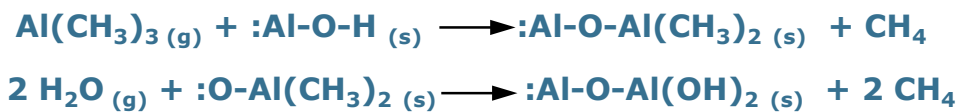


## ALD Cycle for $\text{Al}_2\text{O}_3$



One TMA and one  $\text{H}_2\text{O}$  vapor pulse form one cycle. Here three cycles are shown, with approximately 1 Angstrom per cycle. Each cycle including pulsing and pumping takes e.g. 3 sec.

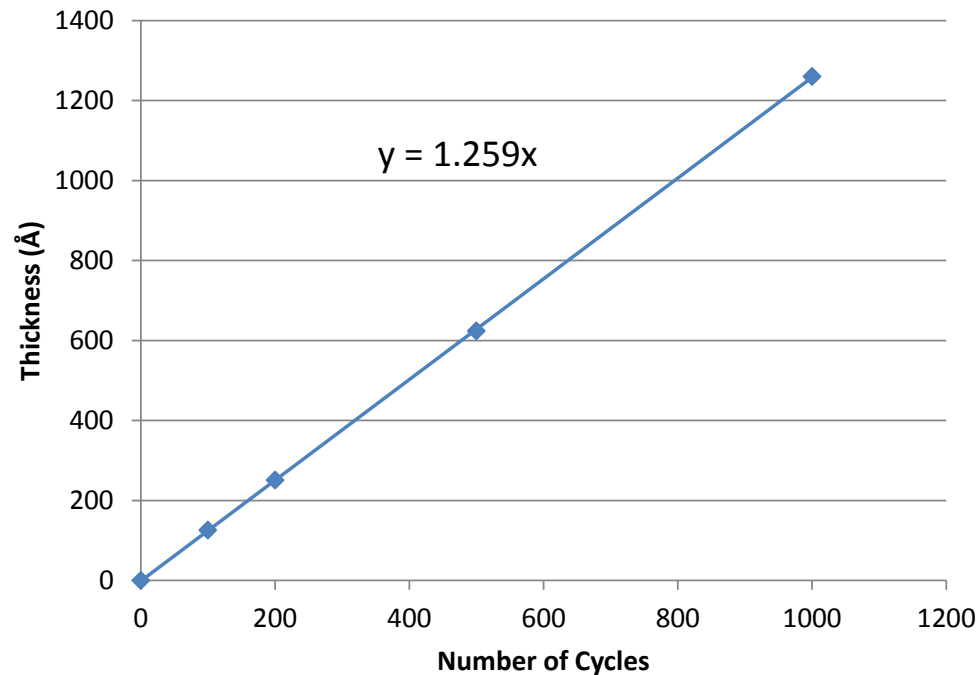
Two reaction steps in each cycle:





# Signature Qualities of ALD

- Step One: Linear growth rate

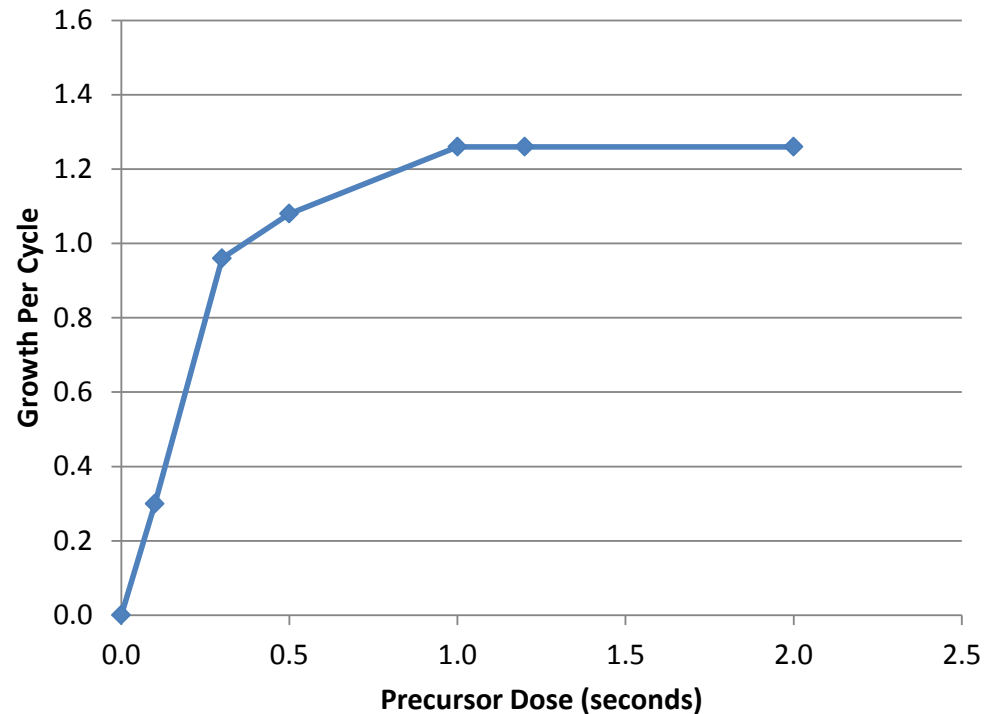




# Signature Qualities of ALD?

- Step Two: Self-limiting deposition/cycle

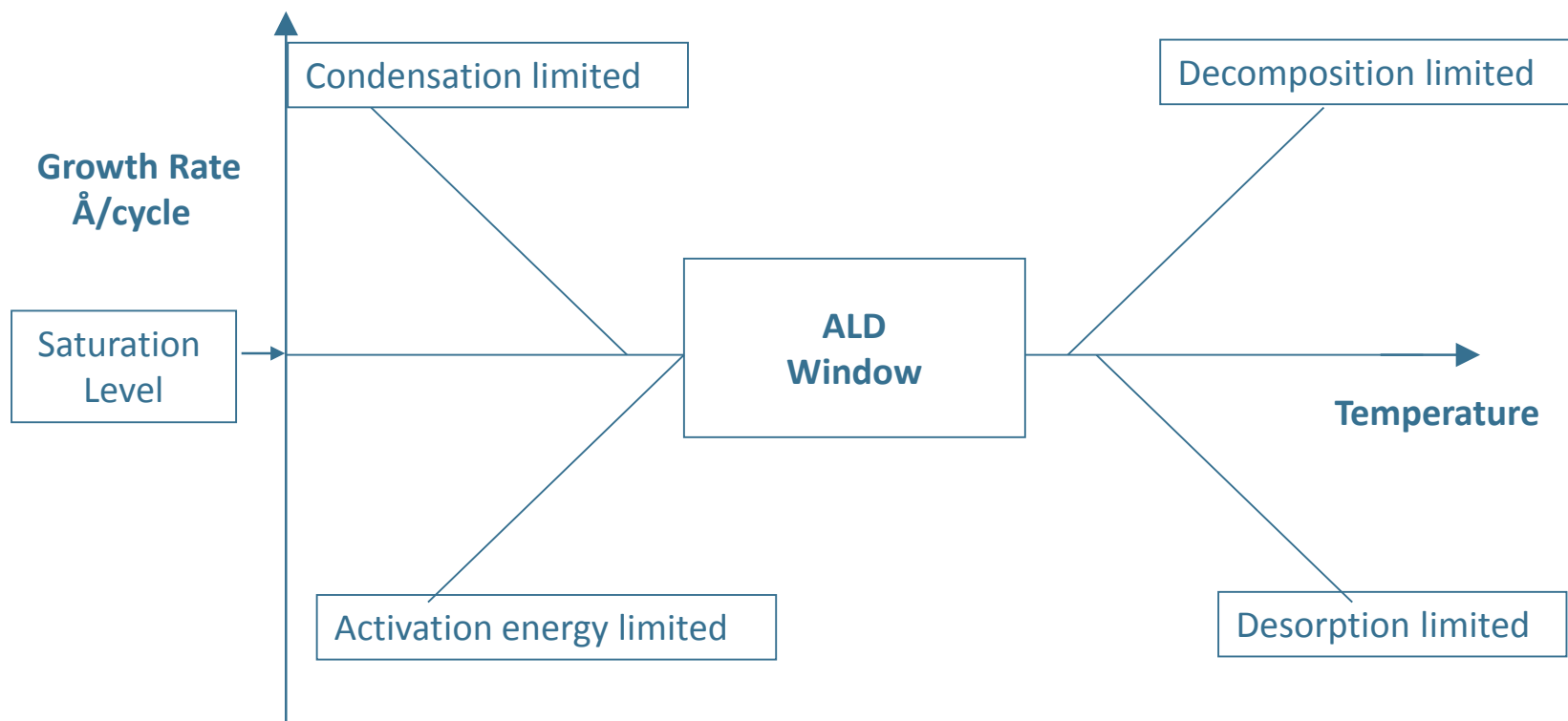
Saturation Curve at 250°C





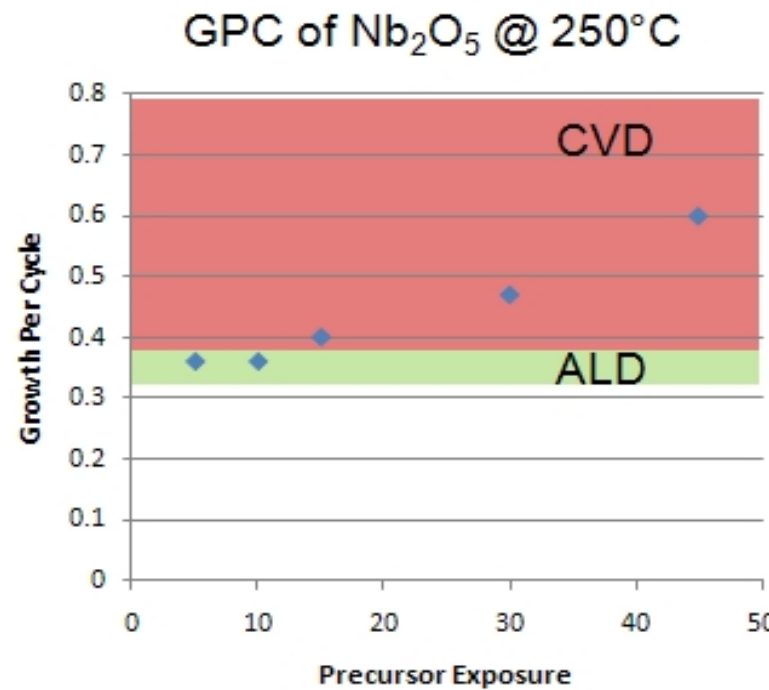
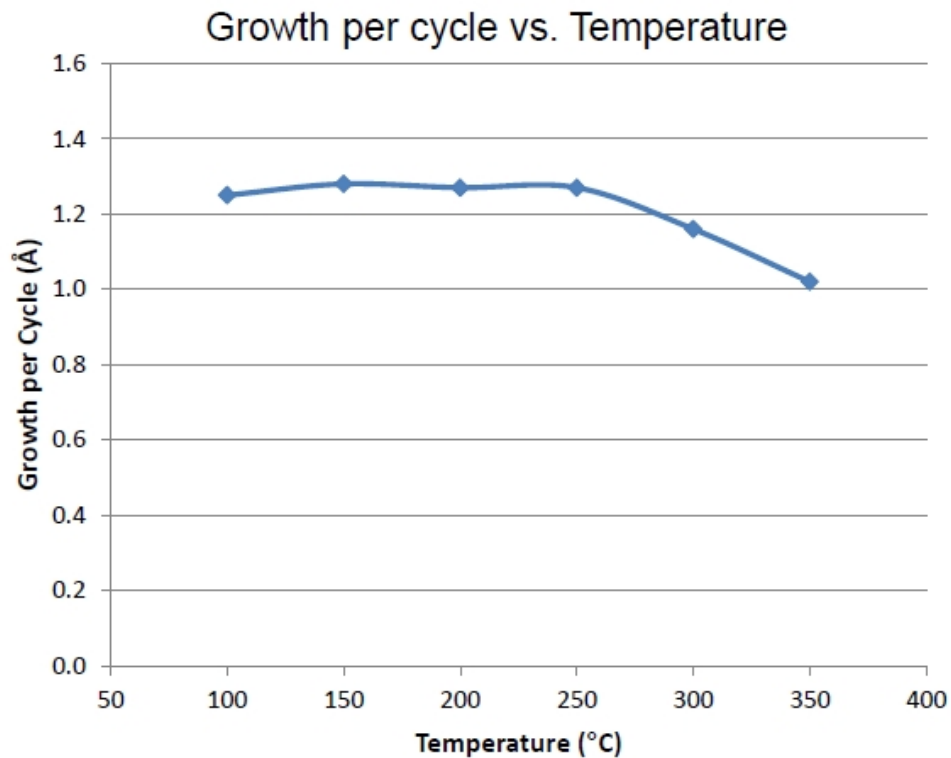
# ALD “Window”

Each ALD process has an ideal process “window” in which growth is saturated at a monolayer of film.





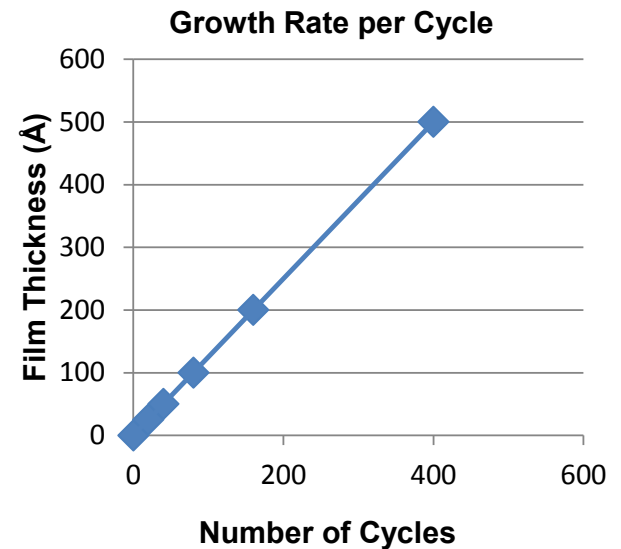
# ALD Window





# Advantages of ALD

- **Unique Chemistry Driven Process**
  - Self-saturating reactions with surface
  - Thermal decomposition of precursor not-allowed
  - Low temperature and low stress (molecular self assembly)
  - Excellent adhesion
- **Conformal Coating**
  - Perfect 3D conformality: no line of sight issues
  - Ultra high aspect ratio (>2,000:1)
  - Large area thickness **uniformity** and **scalability**
- **Challenging Substrates**
  - Gentle deposition process for sensitive substrates (i.e. biomaterials, plastics)
  - Coats challenging substrates (teflon, graphene gold)



Typical ALD processes have a growth rate between 0.5-1.5Å per cycle



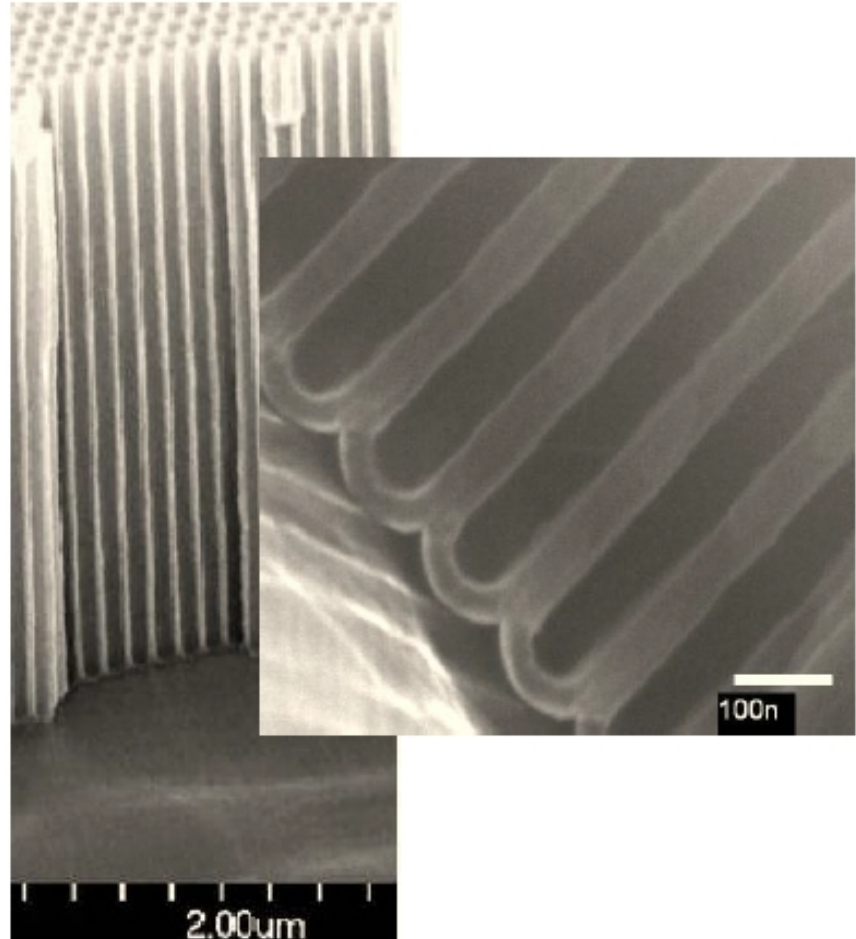
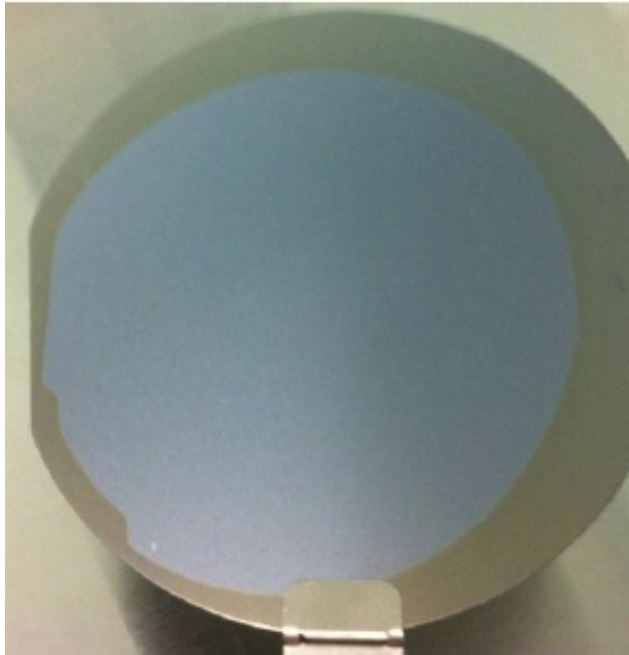
# Disadvantages of ALD

- **Unique, Chemistry Driven Process**
  - Not every material possible
  - Precursors can limit process due to reactivity / availability
  - Process limited by activation energy
  - No thermal decomposition of precursor allowed
- **Conformal Coating**
  - Deposition can be comparably slow: cycles times of 1 second to >1 minute depending on substrate and temperature
  - Removal of excess precursor and by-products is required
- **Challenging Substrates**
  - Functionalization steps may be required





Let's take an extra moment on conformality





# ALD Precursors

Good ALD precursors need to have the following characteristics:

1. Volatility

Vapor pressure ( $> 0.1$ Torr at  $T < 200^{\circ}\text{C}$ )

Liquid at volatilization temperature without decomposition

2. Reactivity

Able to quickly react with substrate in a self-limiting fashion

(most precursors are air-sensitive)

3. Stability

Thermal decomposition in the reactor or on the substrate is not allowed

4. Byproducts

Should not etch growing film and/or compete for surface sites

5. Availability



# ALD Precursors

The second precursor (Precursor B) must react with adsorbed monolayer (A) in order to form bonds and prepare the surface for another dose of (A)

Some common precursors include:

- **Oxidants** – for oxides

Water ( $\text{H}_2\text{O}$ ), ozone,  $\text{O}_2$  plasma, alcohols ( $\text{ROH}$ ), metal alkoxides [ $\text{M}(\text{OR})_x$ ]

- **Reductants**

- Metals

- Hydrogen gas ( $\text{H}_2$ ), ammonia ( $\text{NH}_3$ ),

- ~~Silanes ( $\text{Si}_2\text{H}_6$ )~~

- Nitrides

- Ammonia ( $\text{NH}_3$ ),  $\text{N}_2$  plasma,

- ~~hydrazine ( $\text{NH}_2\text{NH}_2$ )~~

- Sulfides

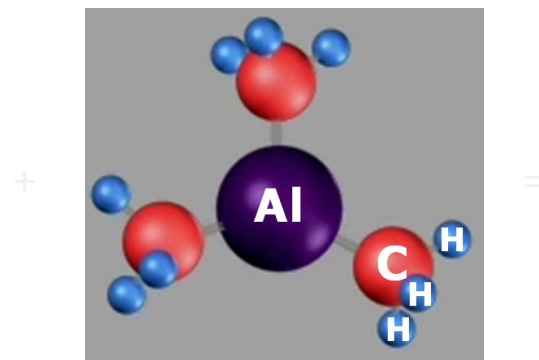
- ~~Hydrogen Sulfide ( $\text{H}_2\text{S}$ )~~





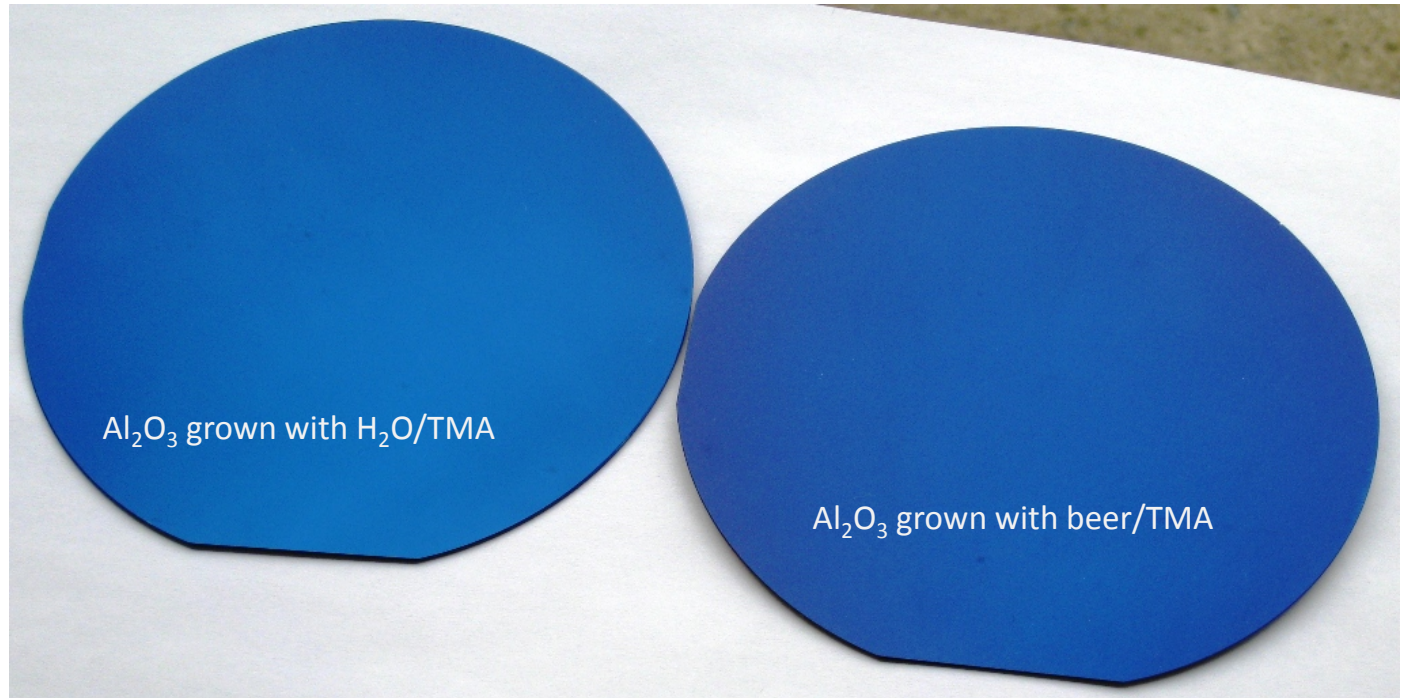
# $\text{Al}_2\text{O}_3$ From Beer

Cambridge NanoTech Experiment: replacement of  $\text{H}_2\text{O}$  with beer





# $\text{Al}_2\text{O}_3$ From Beer

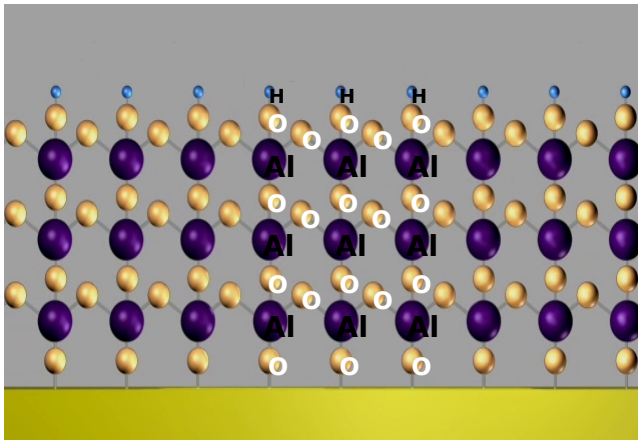


Both 1000 cycles, 1000 Angstrom thick. The results are remarkably similar as the vapor draw allows the water/alcohol vapor to be distilled from the beer precursor cylinder, demonstrating the reduced requirement for high purity precursors if used in certain applications



# Two deviations from the perfect ALD model

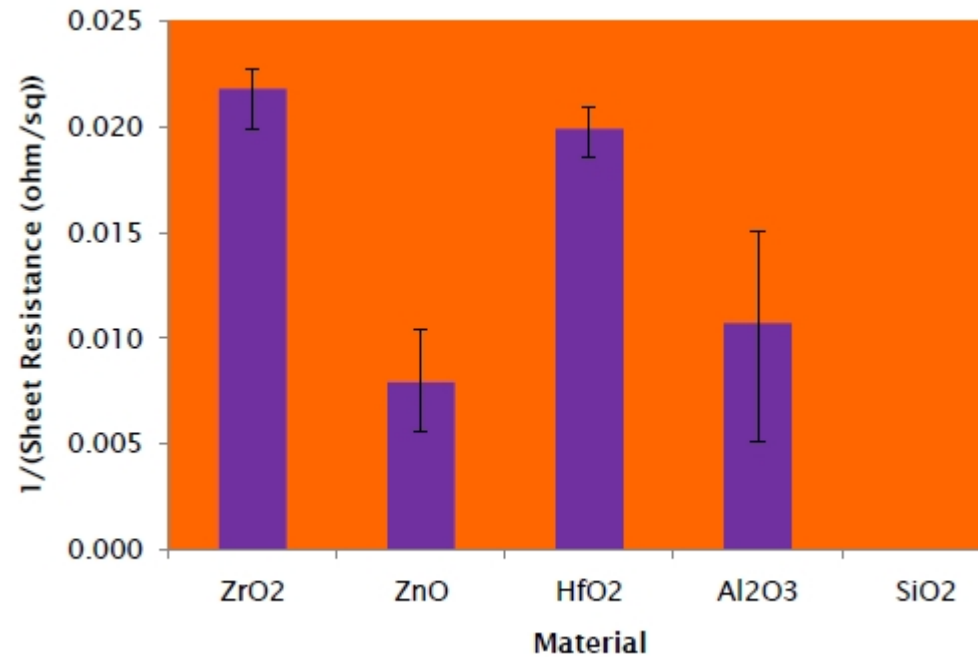
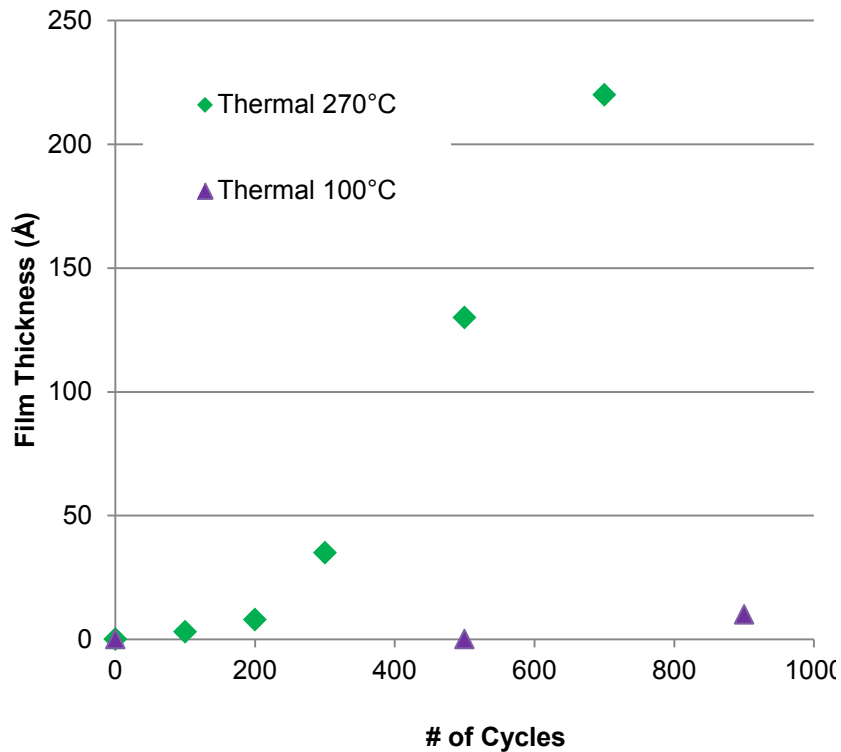
- Films are typically amorphous
  - Poly or crystalline can be achieved in proper deposition condition or with anneal
- Nucleation
  - Not every self-limiting half-reaction fully occupies every available site every cycle
  - In fact, at some level this is true for every film deposited
  - Substrate dependence
  - Chemistry dependence
  - Film roughness





# A little more about nucleation

Pt from  $\text{MeCpPtMe}_3$  and  $\text{O}_2$







# ALD Processes

Cambridge NanoTech has several standard recipes available as starting points for customers. However, there are many processes which have not been attempted in our applications lab.

Many ALD processes exist:

H	Element included in at least one ALD material															He	
Li	Be	Element not included in any ALD material															Ne
Na	Mg																Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac															
			Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	
			Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr	





# Oxides made by ALD

Green = ALD process known for an Oxide of the Element

Red = no process known for ALD of any Oxide of the Element

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac															
			Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	
			Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr	



# Pure Elements made by ALD

**Green = ALD processes known for 16 Pure Elements**

**Red = no process known for ALD of the Element**

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac															
			Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	
			Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr	



# Nitrides made by ALD

**Green = ALD processes known for a Nitride of the Element**

**Red = no process known for ALD of a Nitride of the Element**

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac															
			Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	
			Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr	



# Sulfides made by ALD

**Green = ALD processes known for a Sulfide of the Element**

**Red = no process known for ALD of a Sulfide of the Element**

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac															
			Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	
			Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr	



# Carbides made by ALD

**Green = ALD processes known for a Carbide of the Element**

**Red = no process known for ALD of a Carbide of the Element**

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac															
			Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	
			Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr	



# Fluorides made by ALD

**Green = ALD processes known for a Fluoride of the Element**

**Red = no process known for ALD of a Fluoride of the Element**

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac															
			Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	
			Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr	



H 1																	He 2														
Li 3	Be 4																	B 5	C 6	N 7	O 8	F 9	Ne 10								
Na 11	Mg 12 F																	Al 13 P	Si 14 C	P 15	S 16	Cl 17	Ar 18								
K 19	Ca 20 S	Sc 21	Ti 22 S	V 23	Cr 24	Mn 25 D	Fe 26	Co 27	Ni 28	Cu 29 S D	Zn 30 F D	Ga 31 D	Ge 32	As 33	Se 34	Br 35	Kr 36														
Rb 37	Sr 38 F	Y 39	Zr 40	Nb 41	Mo 42	Tc 43	Ru 44 M	Rh 45	Pd 46 M	Ag 47 M	Cd 48 S	In 49 S P	Sn 50 S D	Sb 51 D	Te 52	I 53	Xe 54														
Cs 55	Ba 56 S	La 57 F	Hf 72 F C	Ta 73	W 74	Re 75	Os 76	Ir 77 M	Pt 78 M	Au 79	Hg 80 S	Tl 81	Pb 82 S D	Bi 83	Po 84	At 85	Rn 86														
Fr 87	Ra 88	Ac 89	Rf 104	Db 105	Sg 106	Bh 107	Hs 108	Mt 109																							
																		Ce 58 D	Pr 59	Nd 60	Pm 61	Sm 62	Eu 63 D	Gd 64	Tb 65 D	Dy 66	Ho 67	Er 68	Tm 69 D	Yb 70	Lu 71
																		Th 90	Pa 92	U 93	Np 94	Pu 95	Am 96	Cm 97	Bk 98	Cf 100	Es 101	Fm 102	Md 104	No 4	Lr 4



# The SNF ALD Websites

<https://snf.stanford.edu/SNF/equipment/chemical-vapor-deposition/ald>

Labmembers Wiki

SNF Directory Site Map Accessibility Contact

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only in current section

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## ALD

Overall review of the ALD systems in the SNF. Savannah: a gold level contamination, thermal Cambridge Nanotech Savannah S200 system. Operational. Fiji1: a clean, plasma and thermal Cambridge Nanotech Fiji F202 chamber with ozone. Operational. Fiji2: an open material, plasma and thermal Cambridge Nanotech Fiji F202 chamber, Operational. Fiji3: a open material, plasma and thermal Cambridge Nanotech Fiji F200 chamber dedicated to oxide depositions. Arriving November 2011, anticipated online in early 2013. Savannah-mvd: a Cambridge Nanotech Savannah S200 system configured for Molecular Vapor Deposition and with the reaction chamber enclosed in an inert glovebox. Arriving November 2011, anticipated online in early 2013. Current SNF ALD film capabilities can be found on the Fiji1, Fiji2, and Savannah pages.

[Savannah](#)

Savannah is a thermal atomic layer deposition (ALD) system. It is a Savannah S200 from Cambridge Nanotech and is categorized as gold contaminated. The system can accommodate pieces up to an 8" wafer.

[Fiji1](#)

Fiji1 is a load-locked, plasma-enabled atomic layer deposition (ALD) system. Coupled with Fiji2, Fiji1 is a Fiji F202 system from Cambridge Nanotech and is capable of both thermal and plasma assisted ALD of various dielectric and metallic films. The system can accommodate pieces up to an 8" wafer. Fiji1 is currently classified as semi-clean.

[Savannah Images](#)

Images for the savannah information page

[Fiji Images](#)

Images for the documentation of both Fiji-L and Fiji-R.

[map of fiji-l and fiji-r location in snf](#)

[Fiji2](#)

Fiji2 is a load-locked, plasma-enabled atomic layer deposition (ALD) system. Coupled with Fiji1, Fiji2 is a Fiji F202 system from Cambridge Nanotech and is capable of both thermal and plasma assisted ALD of various dielectric and metallic films. The system can accommodate pieces up to an 8" wafer. Fiji2 is currently classified as gold contaminated and is open to a wide range of materials.

<https://snf.stanford.edu/SNF/equipment/chemical-vapor-deposition/ald>

## Possible Films

The films available on the Savannah is determined by the precursors installed in the system. The list of available precursors is maintained on this page and also on a file on the desktop of control computer. The file on the computer is the final word on what precursors are installed on the system currently. In the event that this website and the file on the computer disagree - follow the document on the control computer.

### Current films available (in stock precursors):

Film	NOTES	Tools	Deposition rate (Å/cycle) @ temp	Thickness Nonuniformity over 2 100mm wafers	Precursor 1	Precursor 1 temperature	Precursor 2
Thermal Al <sub>2</sub> O <sub>3</sub>	Well characterized	Fiji1, Fiji2, Savannah	1 @ 200C	1%	Trimethylaluminum	Unheated	H <sub>2</sub> O
Plasma Al <sub>2</sub> O <sub>3</sub>	Well characterized	Fiji1, Fiji2	1 @ 200C	0.50%	Trimethylaluminum	Unheated	O <sub>2</sub> plasma
Thermal TiO <sub>2</sub>	Being characterized	Fiji1, Fiji2, Savannah	0.4	1%	Tetrakis(dimethylamido)titanium(IV)	75C	H <sub>2</sub> O
Plasma TiO <sub>2</sub>	Being characterized	Fiji1, Fiji2	0.4	2%	Tetrakis(dimethylamido)titanium(IV)	75C	O <sub>2</sub> plasma
Plasma TiN	Well characterized	Fiji1, Fiji2	0.5		Tetrakis(dimethylamido)titanium(IV)	75C	N <sub>2</sub> plasma
Plasma WN	In development	Fiji1, Fiji2			Bis(ter-butylimino)bis(dimethylamino)tungsten(VI)	60C (TBD)	N <sub>2</sub> plasma
Thermal HfO <sub>2</sub>	Well characterized	Fiji1, Fiji2, Savannah	1.0	1%	Tetrakis(dimethylamido)hafnium	75C	H <sub>2</sub> O
Plasma HfO <sub>2</sub>	Well characterized	Fiji1, Fiji2	1.0	1%	Tetrakis(dimethylamido)hafnium(IV)	75C	O <sub>2</sub>
Thermal ZrO <sub>2</sub>	In development	Fiji1, Fiji2, Savannah	0.8	1%	Tetrakis(dimethylamido)zirconium(IV)	75C	H <sub>2</sub> O

<https://snf.stanford.edu/SNF/equipment/chemical-vapor-deposition/ald/savannah>

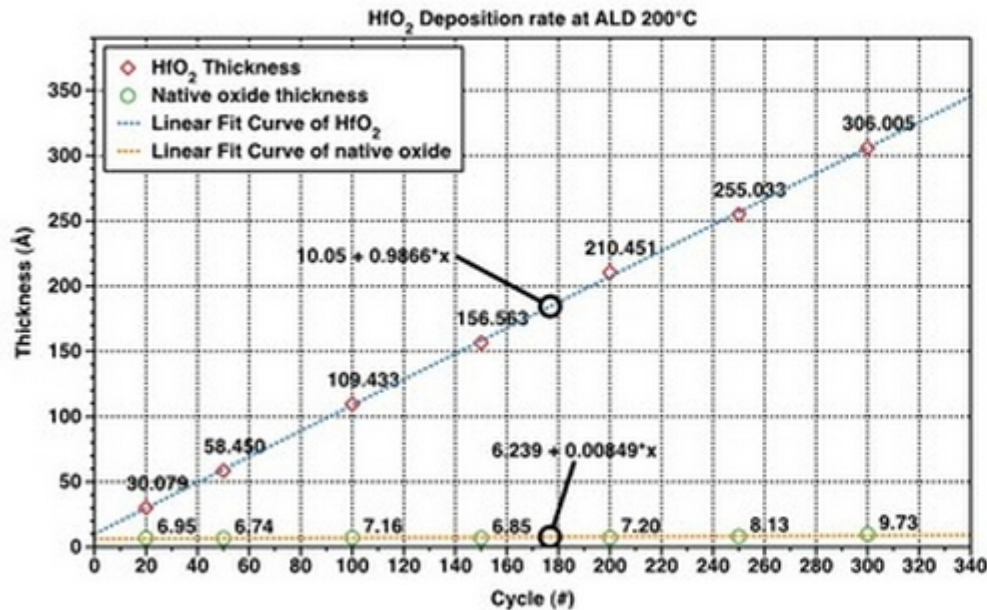




# SNF ALD Websites

## HfO<sub>2</sub> Deposition rate of .99A/cycle for standard recipe

(Thanks to Woo-Shik Jung and for his help with data collection.)



Deposition rate of Hafnia ALD at 200C (note the native oxide of the Si wafer was also tracked and plotted on this graph)



# Background Summary

- Atomic Layer Deposition can deliver thin films with
  - Very precise thickness control ( $\sim$ Angstroms)
  - Many materials (metals, dielectrics, magnetics...)
  - Highly conformal
  - Uniform over large areas
  - Engineerable into “meta-materials” with alternating layers
- Downside:
  - Slow slow slow
  - Not all chemistries are created equal
  - Nucleation



# Any Questions?

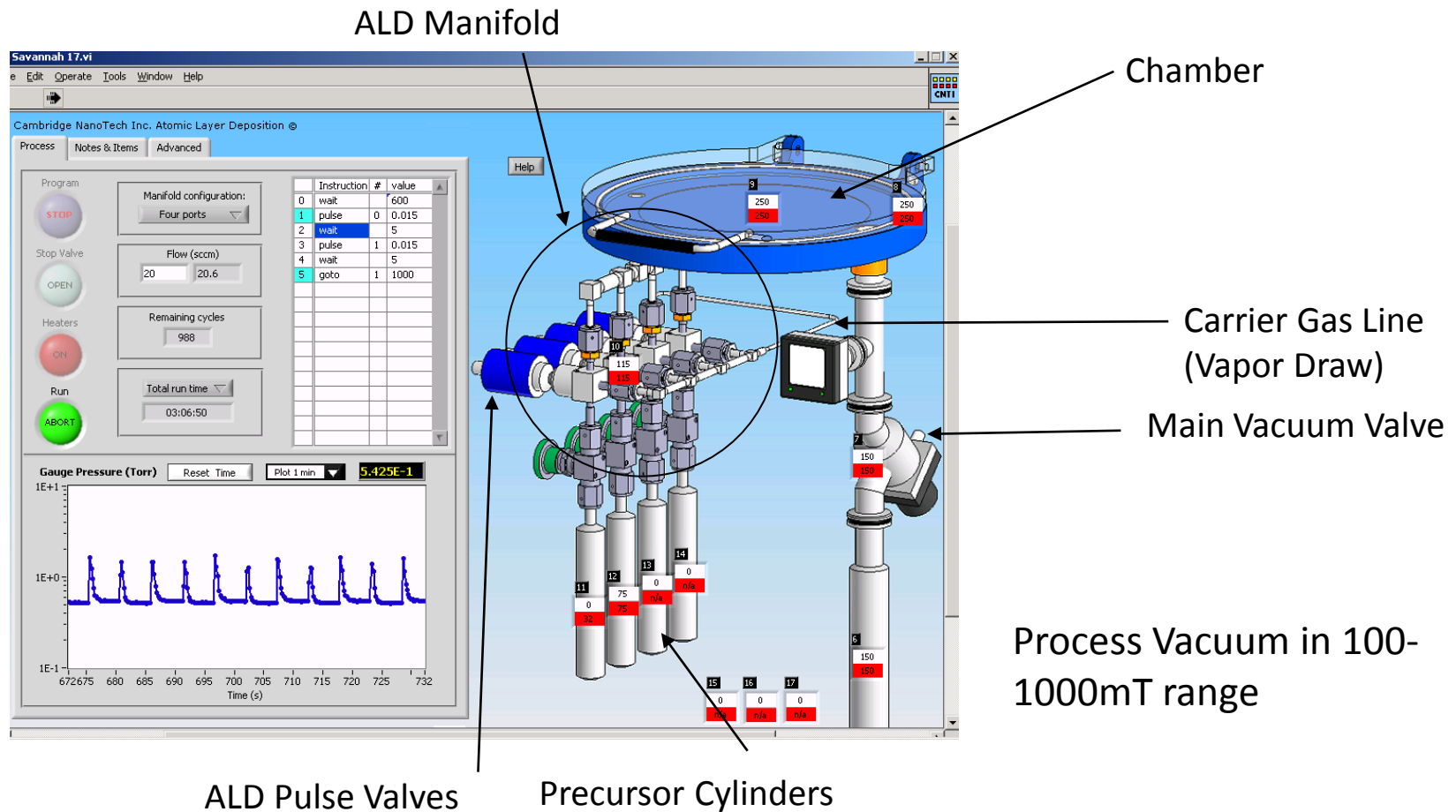


# The Cambridge Nanotech Savannah





# Main Components of an ALD System





# Writing a Recipe

- A sequential list of commands
- Basic recipe
  - Length of precursor pulse
  - Length of purge cycle
  - Temperature of reactor and other components
  - # of cycles

Step	command	#	Value	units
0	heater	8	200	C
1	heater	9	200	C
2	Flow		20	sccm
3	Pulse	0	0.02	Sec
4	wait		15	Sec
5	pulse	1	0.015	sec
6	Wait		15	Sec
7	goto	3	100	Cycles
8	flow		5	sccm

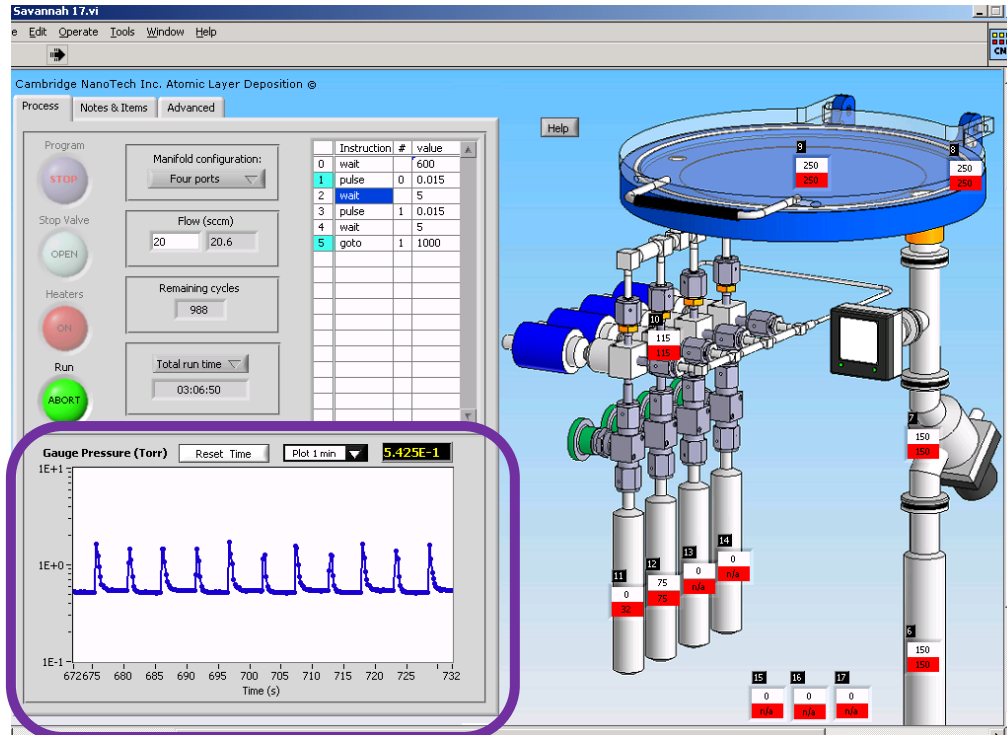


# Other recipe variables

- Stabilize
  - Select a heater and a temperature
  - The system waits to proceed until the heater maintains that value for a few seconds
  - Allows consistent processing
- Stop-valve
  - Boolean command to control the gate valve to the pump
  - By temporarily valving off the pump you can leave the reactants in the chamber longer
  - This can enhance coverage of extreme aspect ratios (2000:1)



# What you can tell from the pulse train



Missing pulses indicate a problem  
Most likely the precursor is out (should last 1000s of pulses before refilling/replacing)

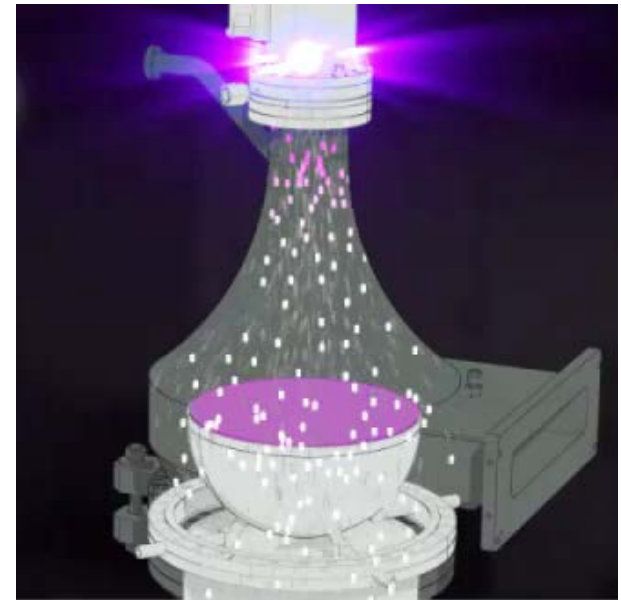
Height above base pressure should be  $\sim 100$  mTorr for chamber saturation





# Plasma Enabled (PE)ALD

- **Remote Plasma as a reactant**
  - Widens ALD window for materials by decreasing activation energy
  - Avoids precursor decomposition or damaging substrates with limited thermal budget
  - Remote ICP source prevents substrate damage from ions
  - Faster deposition cycle times
  - Fewer contaminants in films
  - Smaller nucleation delay
- **Film Examples**
  - Low temperature oxides
  - Metal nitrides
  - Metallic films
- **High-Aspect Ratio Structures**
  - Radical recombination prevents greater than ~20:1



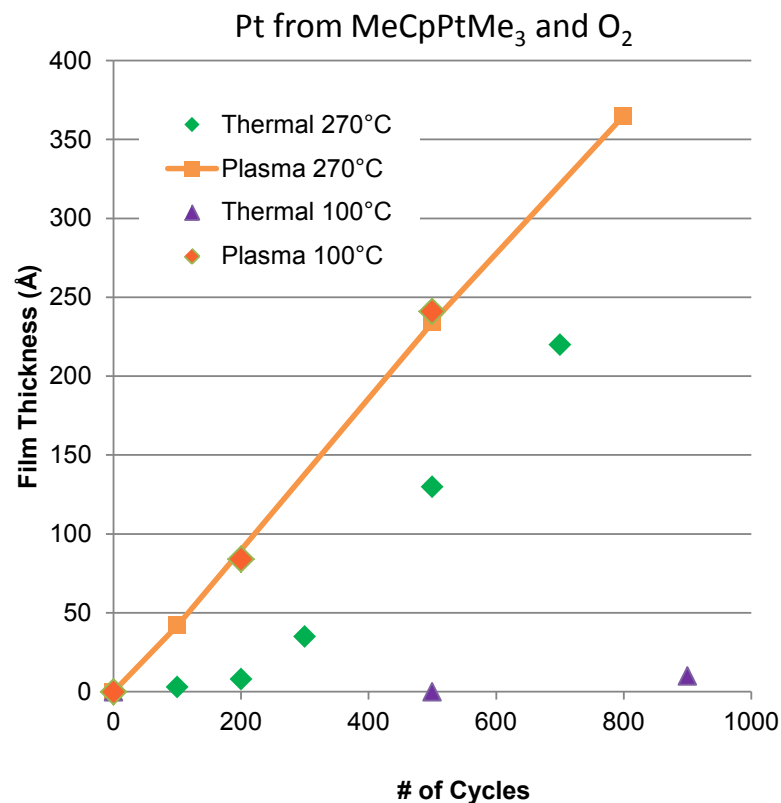
Fiji PE-ALD chamber



# Benefits of Plasma

Decreased nucleation for metallic films

- Precursor temp 90°C
- Nucleation is eliminated when using O<sub>2</sub> plasma as reactant
- Constant growth rate per cycle even at low process temp





# The Cambridge Nanotech Fiji



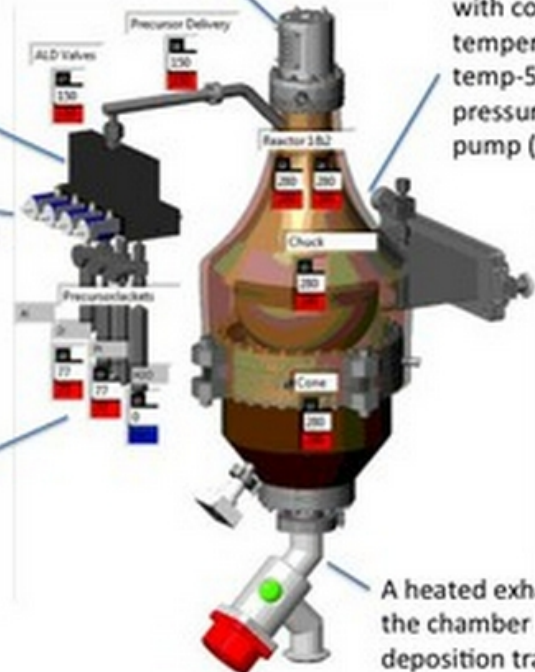
A heated manifold that conducts the precursors into the reaction chamber via a carrier gas (we use the house, high purity Ar)

High speed ALD valves that control the release of precursors into the manifold for introduction to the reaction chamber

A set of precursor canisters

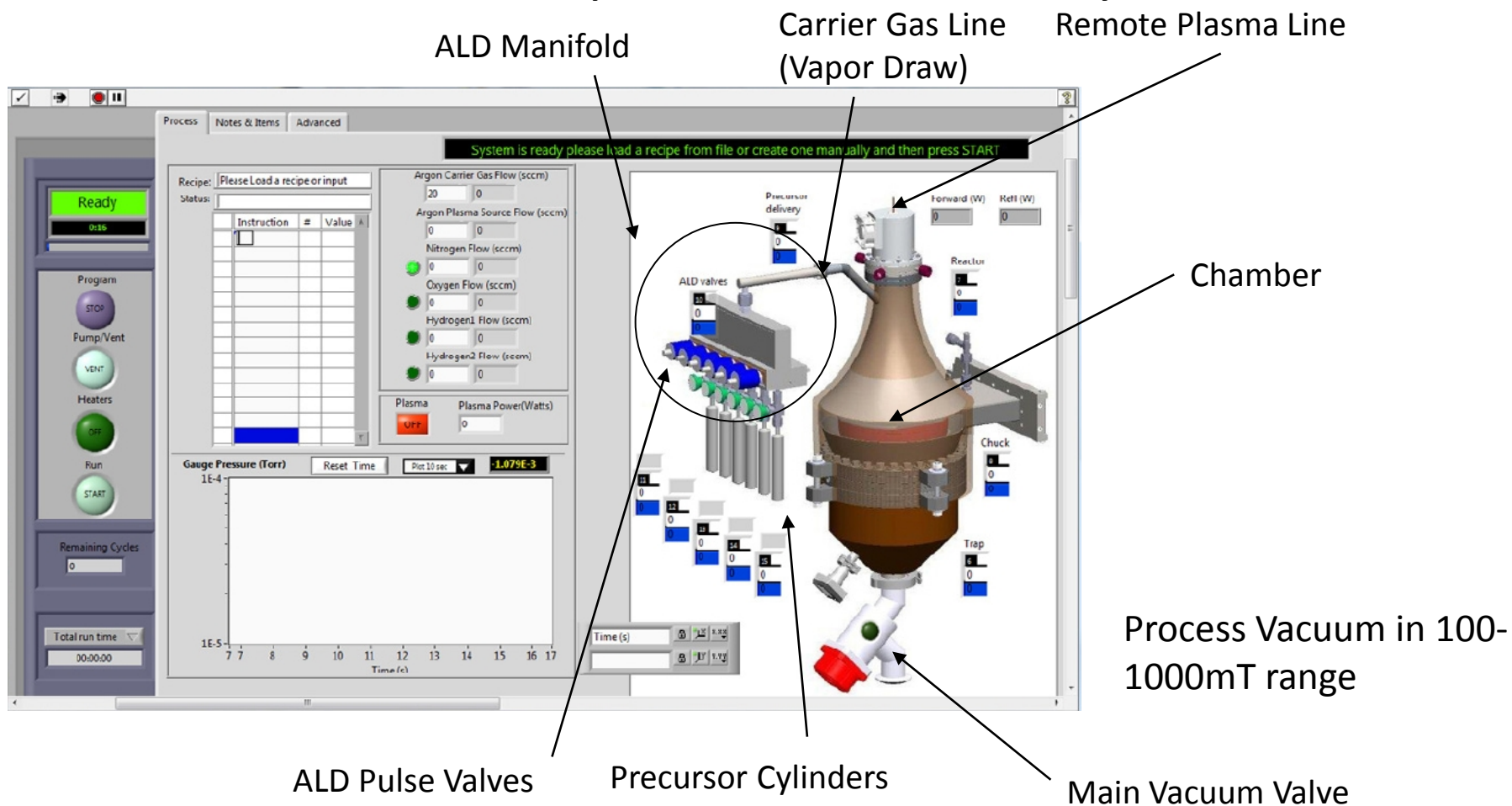
An RF plasma generator capable of producing 300W of power.

The reaction chamber with controllable temperature (room temp-500C) and variable pressure controlled by pump (.05-1Torr).





# Main Components of an ALD System





# Writing a Recipe

- A sequential list of commands
- Basic recipe
  - Length of precursor pulse
  - Length of purge cycle
  - Temperature of reactors etc
  - **Process gas flows**
  - **Plasma power**
  - **# of cycles**

Instruction #	Value	Units	
0	flow	0 20 sccm	Flow carrier gas (0) at 20 sccm
1	flow	1 40 sccm	Flow plasma gas (1) at 40 sccm
2	heater	12 250 C	Set heater 12 (Cone heater) to 250°C
3	heater	13 250 C	Set heater 13 (Reactor Heater 1) to 250°C
4	heater	14 250 C	Set heater 14 (Reactor Heater 2) to 250°C
5	heater	15 250 C	Set heater 15 (Chuck heater) to 250°C
6	stabilize	12	Wait for heater 12 to stabilize at setpoint
7	stabilize	13	Wait for heater 13 to stabilize at setpoint
8	stabilize	14	Wait for heater 14 to stabilize at setpoint
9	stabilize	15	Wait for heater 15 to stabilize at setpoint
10	wait	300 sec	Wait 300 seconds (5 minutes for system to stabilize)
11	flow	0 60 sccm	Increase carrier gas flow to 60 sccm
12	flow	1 200 sccm	Increase plasma gas flow to 200 sccm
13	MFCvalve	3 1	Open MFC valve # 3 (oxygen)
14	wait	20 sec	Wait 20 seconds
15	pulse	1 0.06 sec	Pulse ALD 1 for 0.06 seconds
16	wait	5 sec	Wait 5 seconds for carrier gas to flow through system
17	flow	3 20 sccm	Flow MFC 3 (oxygen) at 20 sccm
18	wait	5 sec	Wait 5 seconds
19	plasma	300 Watts	Set plasma power to 300 Watts
20	wait	20 sec	Wait 20 seconds
21	plasma	0 Watts	Turn off plasma power
22	flow	3 0 sccm	Turn off MFC 3 (oxygen) gas flow
23	wait	5 sec	Wait 5 seconds
24	goto	15 200 cycles	Goto step 15 (pulse) and repeat steps 15-23. Repeat for a total of 200 times
25	flow	0 20 sccm	Reduce carrier gas to idle flow of 20 sccm
26	flow	1 40 sccm	Reduce plasma gas flow to idle flow of 40 sccm
27	MFCvalve	3 0	Close MFC valve # 3 (oxygen)

Parameter	Notes
Heater	Each heater has an unique item number and a value given in degrees Celsius. Do not overheat precursors (all precursors should be below 115C and some should not be heated at all - consult with quality circle if unsure). The reaction chamber should always be hotter than the manifold which should always be hotter than the precursor lines. The upper limits on temperature are protected by setpoints internal to the system.
Flow	This controls the flow of through a number of MFC. The plasma process gases are controlled by these MFCs as are the carrier gases. It is defined in sccm. It is not recommended to adjust the standard flow values in recipes. The MFCs for H <sub>2</sub> , N <sub>2</sub> , and O <sub>2</sub> additionally have a hard off state and should be set to zero and then closed. This is already established in all recipes on the tool.
Pulse	This command is for pulsing a precursor line. It requires an ALD valve number and the amount of time you want the valve open in seconds. The fastest these valves can fire is roughly .015 seconds, so note that even if you define a shorter time that is likely the valve open time you will get. (NOTE: when writing a recipe the time in seconds needs a digit to the left of the decimal place; thus you should use "0.015" instead of ".015" for the minimum duration pulse.)
goto	Used to define loops in the recipes. This command takes as an input the step to which the recipe should return. The value for this command defines how many times the loop will run.
stabilize	This command is used to hold a recipe until a heater has reached the desired value. It takes as input a heater ID number and will wait until that heater demonstrates the set temperature with a degree C over a few seconds.
wait	This command takes as input a value in seconds that you would like the system to wait before proceeding to the next command. (NOTE: when writing a recipe the time in seconds needs a digit to the left of the decimal place; thus you should use "0.015" instead of ".015" for the minimum duration pulse.)
plasma	This command indicates the power that should be generated by the RF plasma system in Watts.
stopvalve	This command will close or open the output valve for the reaction chamber depending on a Boolean input. This command is currently not used in any of the standard recipes, but development is beginning for recipes using this feature.
line ac out	Users should not use this command. It changes the heater voltage on precursor heater wraps.

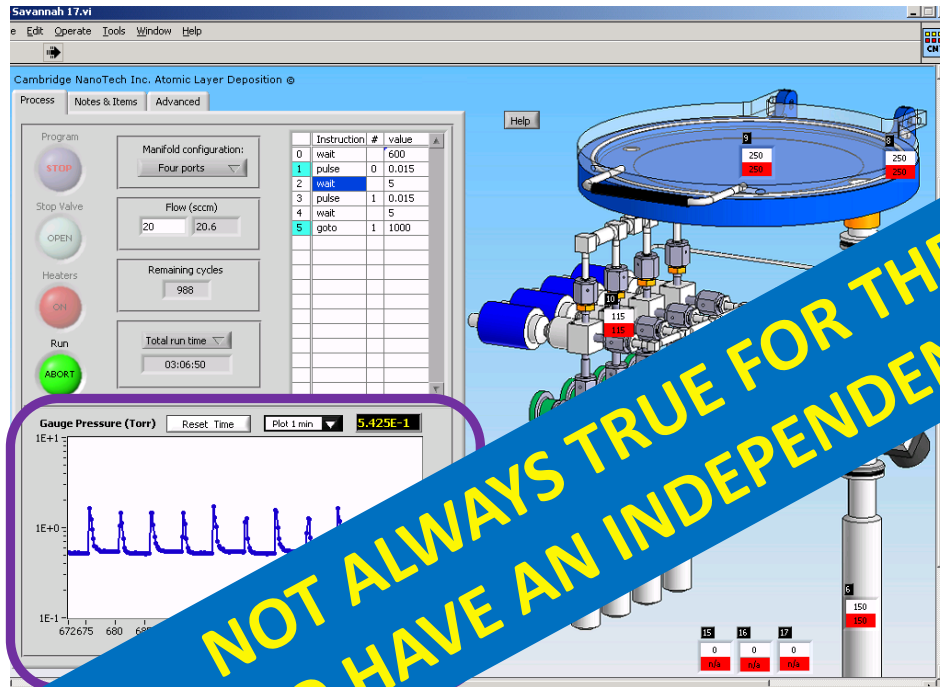


# Other recipe variables

- Stabilize
  - Select a heater and a temperature
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# What you can tell from the pulse train



**NOT ALWAYS TRUE FOR THE FIJI!**  
**ESSENTIAL TO HAVE AN INDEPENDENT MEASUREMENT**

Missing  
in  
the  
cursor is out  
(should last 1000s  
of pulses before  
refilling/replacing)

base pressure should be  
10<sup>-10</sup> Torr for chamber saturation





# Final thoughts

- The field is rapidly changing
  - More precursors
  - More materials
  - More variations
  - More applications
- Like most Nanofabrication...
  - Best chance for success is to get in the lab and push experiments
- Some resources:
  - [www.cambridgenanotech.com](http://www.cambridgenanotech.com)
  - [snf.stanford.edu/SNF/equipment/chemical-vapor-deposition/ald/](http://snf.stanford.edu/SNF/equipment/chemical-vapor-deposition/ald/)
  - <https://snf.stanford.edu/SNF/equipment/chemical-vapor-deposition/ald/fiji-l>
  - [jprovine@stanford.edu](mailto:jprovine@stanford.edu); [mmrincon@stanford.edu](mailto:mmrincon@stanford.edu)





Thank you.

Any Questions?