NCCAVS 2018

TOOL DESIGN CONSIDERATIONS FOR ADVANCED ATOMIC LAYER DEPOSITION

Duane Bingaman V.P. Process Equipment
Kurt Lesker Company

- Brief Introduction to ALD
- ALD Process Chamber Design
  - Perpendicular & Cross Flow Design Concepts
  - Key Features of Interest and Design Challenges
  - In-Situ Ellipsometry
- ALD Process Chamber Overview
  - Precursor & Inactive Gas Dispersion
  - Gas Flow Dynamics – Precursor Focusing Technology™
- Plasma Considerations
  - Remote vs Direct Plasma
- Thermal Management and Maintenance
  - Parasitic CVD
  - Line condensation and maintenance
- UHP Vacuum Design
- Summary

Atomic Layer Deposition (ALD) is:

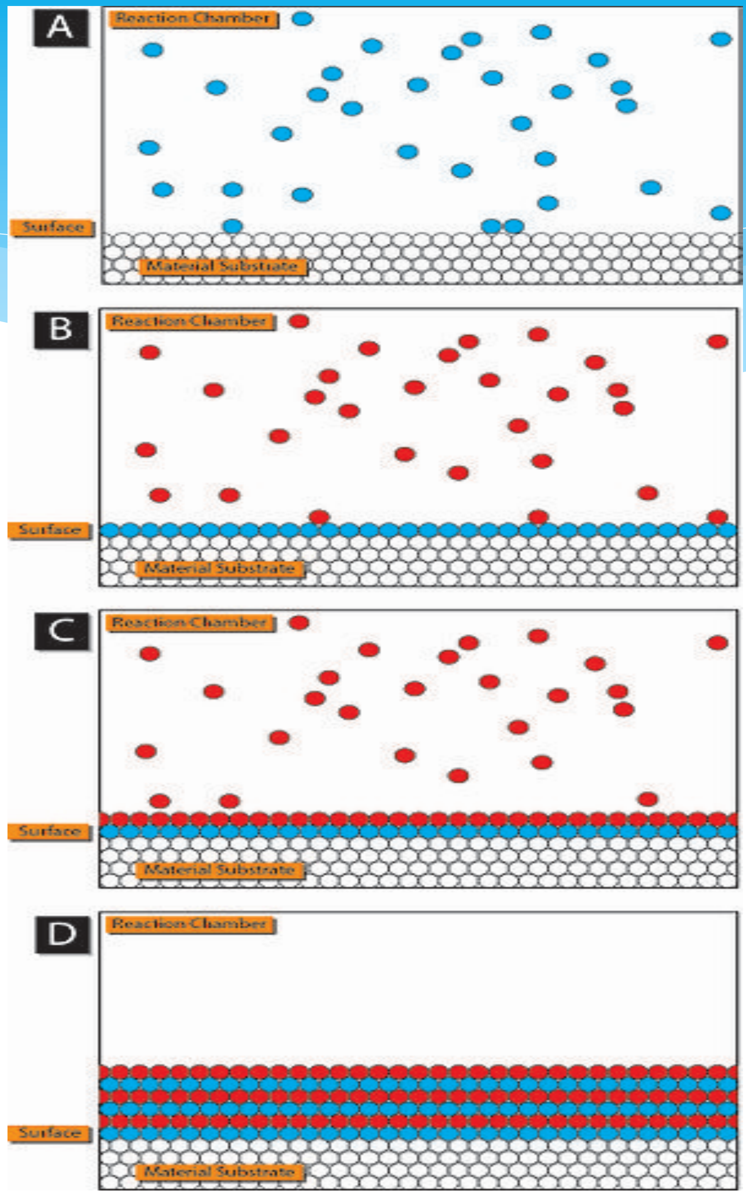
* Thin film deposition
* Based on the sequential use of a gas phase chemical process
* Self limiting, chemical vapor deposition process

A. Precursor introduction, adsorption, and purge

B. 2nd precursor is added

C. Chemical reaction occurs, purge

D. Repeat to desired film thickness



MANY APPLICATIONS

* DRAM capacitors
* Biomedical
* Microelectronics
  * Gate oxides
  * Transition metals nitrides (TiN,TaN)
  * Metals
* Solar
* Energy Storage/Thin film battery
* Encapsulation
* 3D nanofabrication
* Nanophotonics

ADVANTAGES/DISADVANTAGES

+

* Highly Controllable/Slow
* Highly conformal
* Great film uniformity
* Low temperature processes
* Tunable film composition (Hf-H2O-Hf-H20-Zr-H2O)…(Hf-H20-Zr-H2O)

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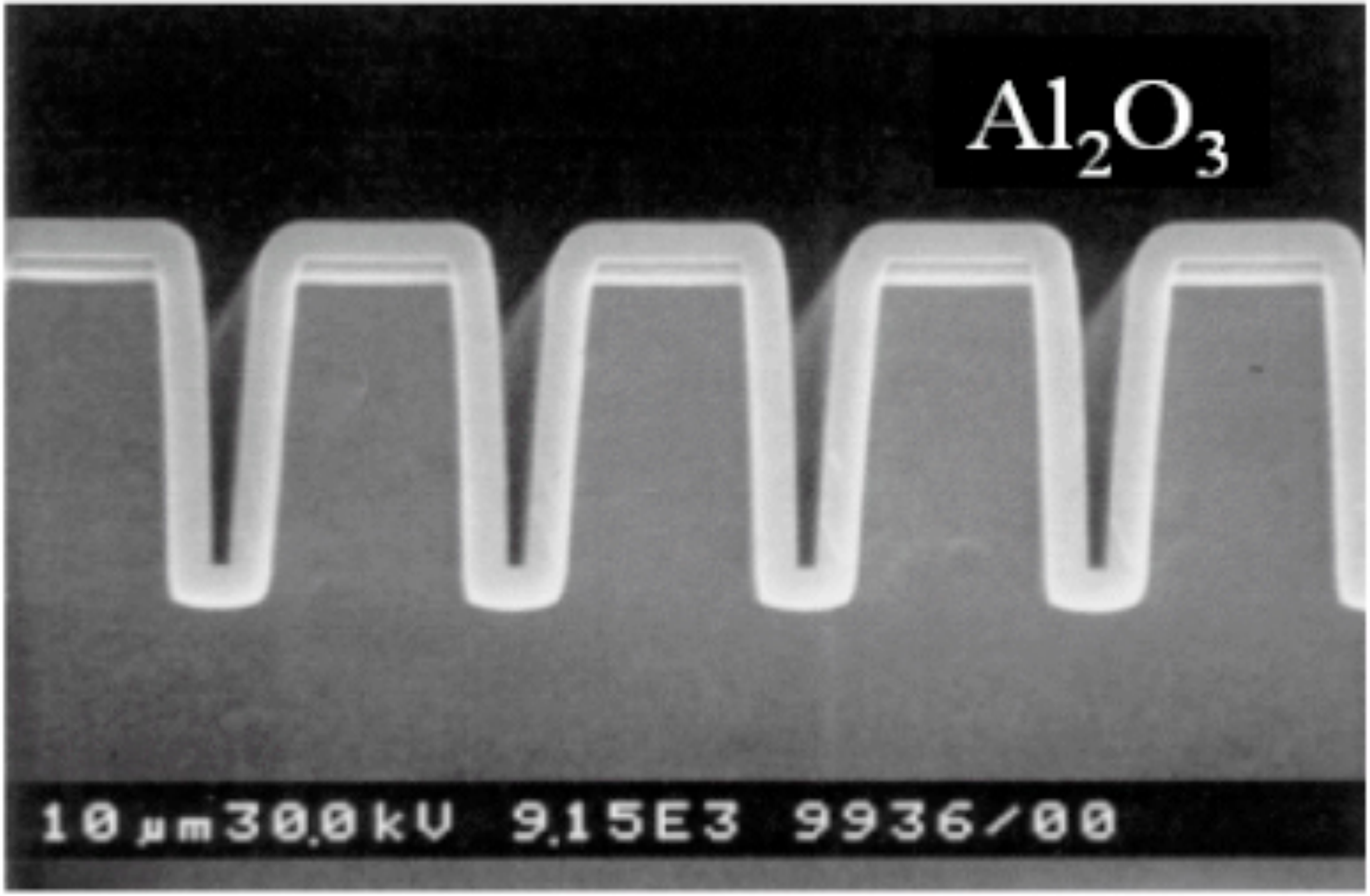
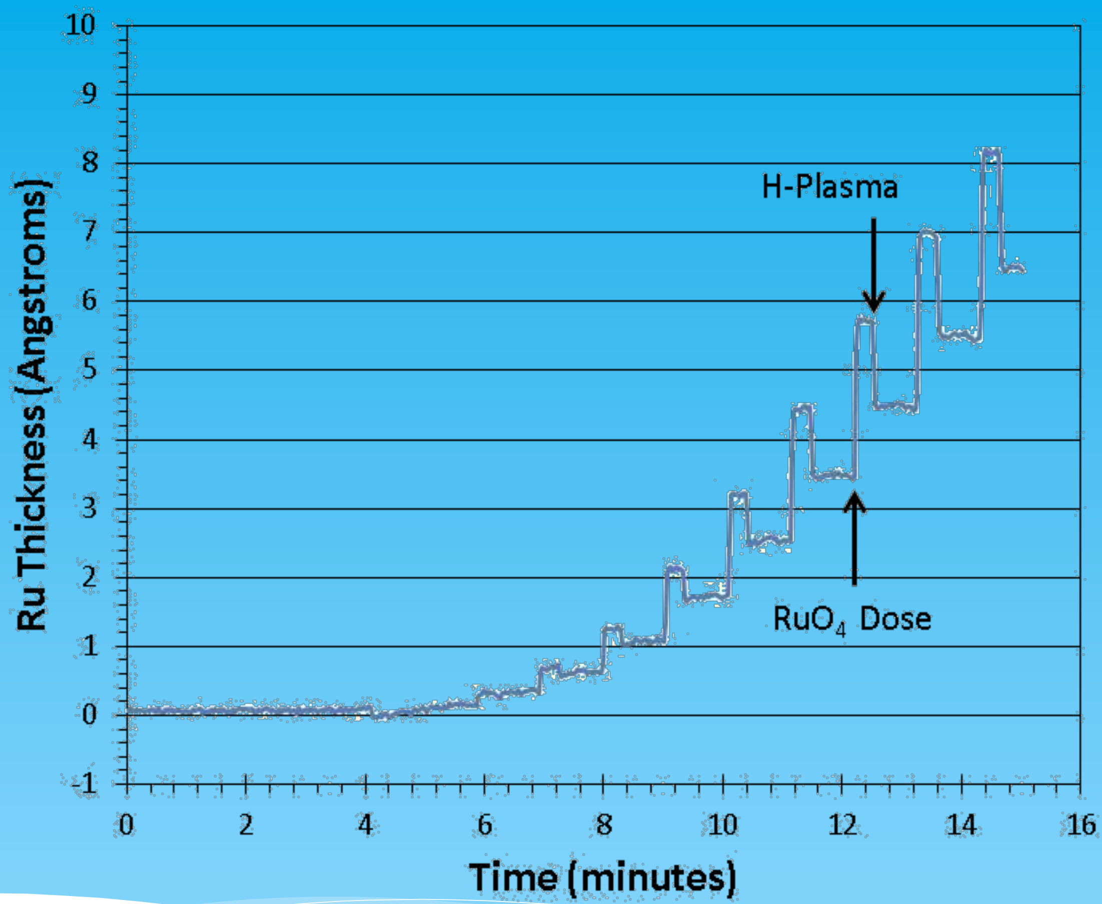
* Slow
* Material limitations
* Parasitic reactions can occur

Conformal

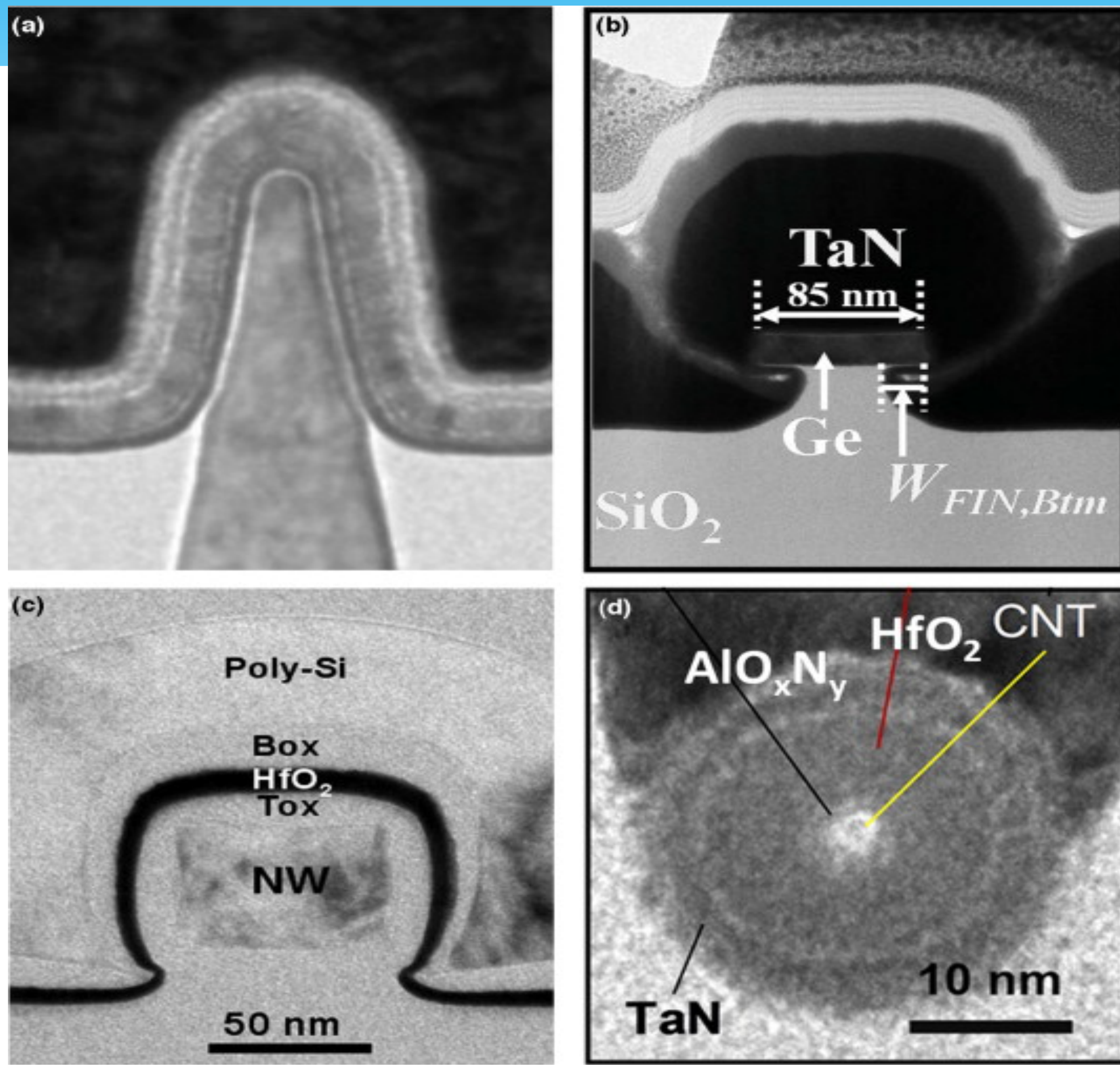


Controllable: Example of In-Situ Spectroscopic Ellipsometry



Initial stages of Ru PEALD using RuO_4 and H-plasma at 100°C

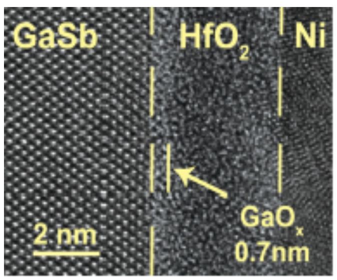
Compound Materials, Complex Geometries

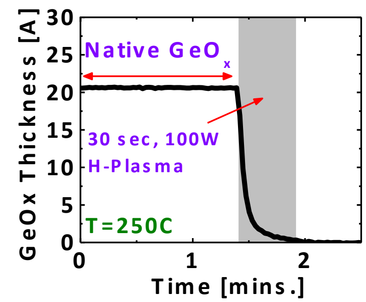


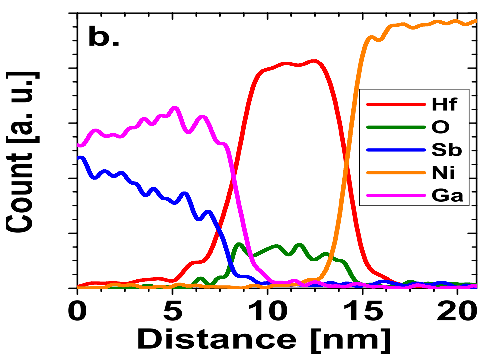
Kurt J. Lesker Company

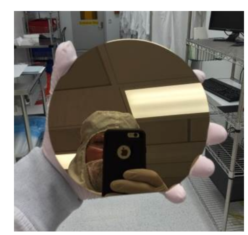
ALD-150LX

ALD Processing for Advanced R&D Applications



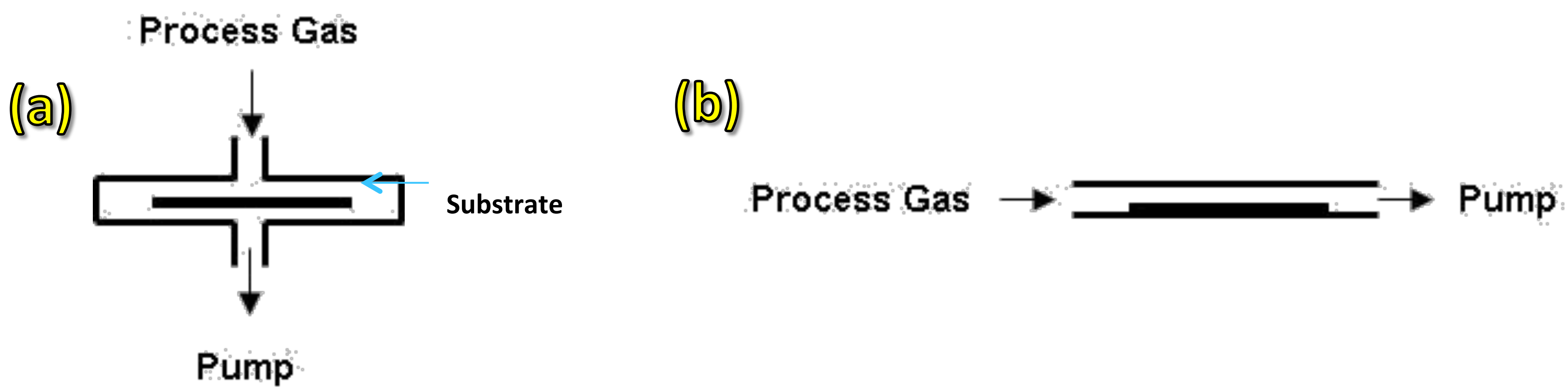






ALD Process Chamber Design

Schematic representations of (a) perpendicular & (b) cross flow chamber design concepts for single wafer processing



- Key benefit of perpendicular flow design is superior gas flow uniformity across substrate surface
- Benefits of cross flow design include simplicity & minimal volume requirements

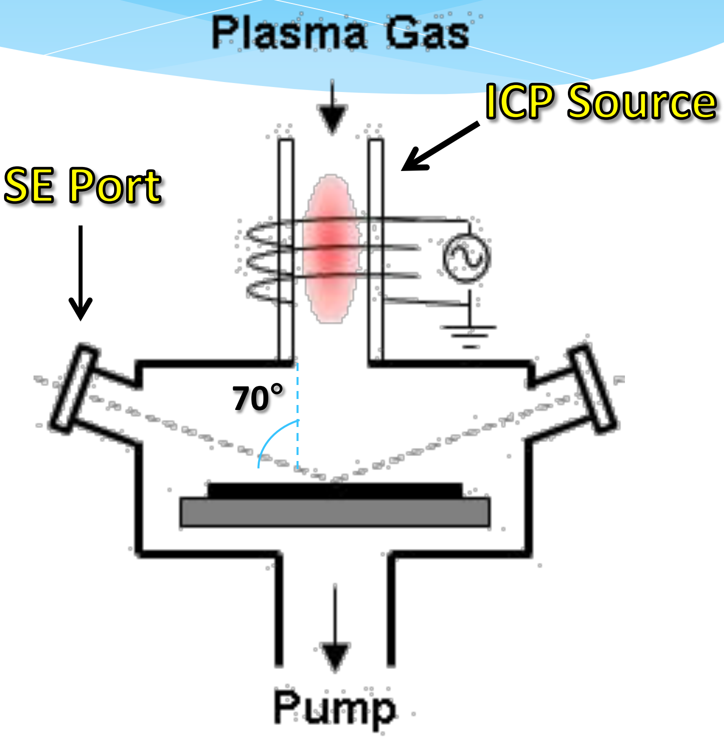
Optimum design is driven by key features of interest

Key Features of Interest

- *Integration of remote inductively coupled plasma (ICP)*
- *In-situ spectroscopic ellipsometry (SE)*

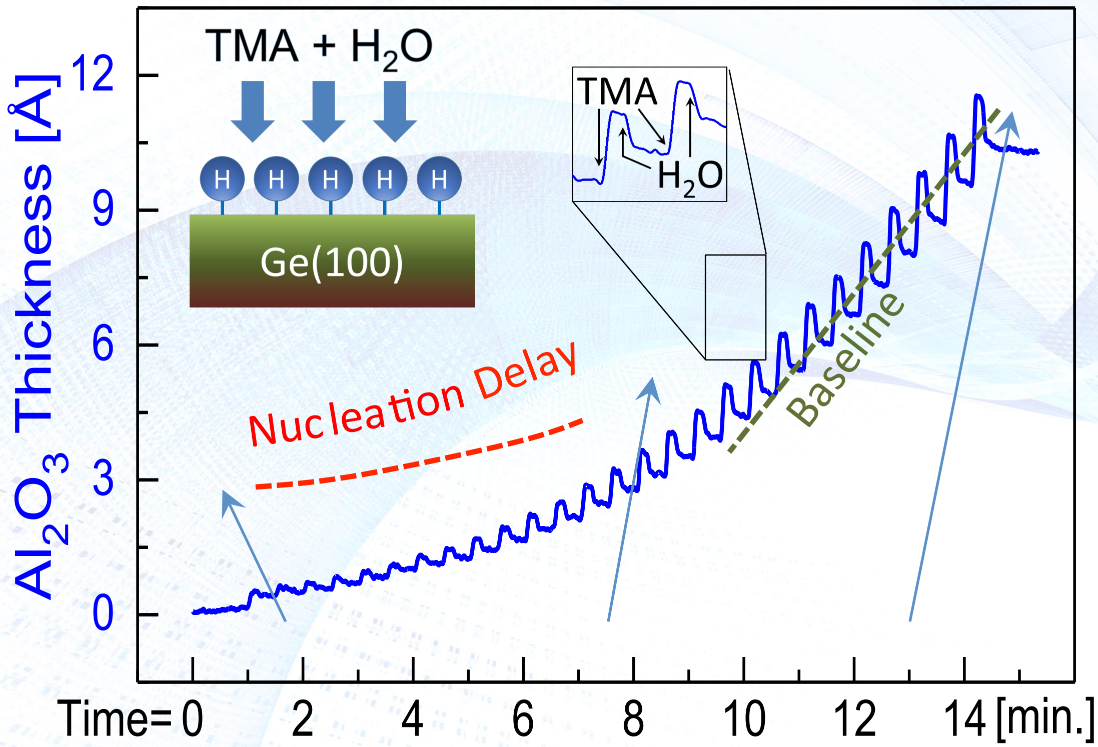
❖ Remote ICP requires distance & volume to avoid direct exposure and promote plasma density & uniformity across substrate surface

❖ Spatial requirements of remote plasma work nicely with space required for Ellipsometry port integration



Perpendicular flow design is ideal for integration of these key features

Al_2O_3 ALD Nucleation on Hydrogenated Ge Surface

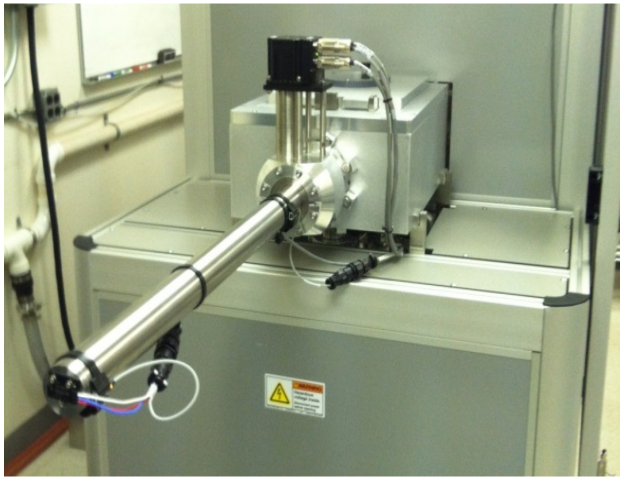


- ❑ Low precursor adsorption in initial cycles → local ALD reaction on Ge: H surface
- ❑ Obvious nucleation delay on hydrogenated Ge surface until ~25 cycles

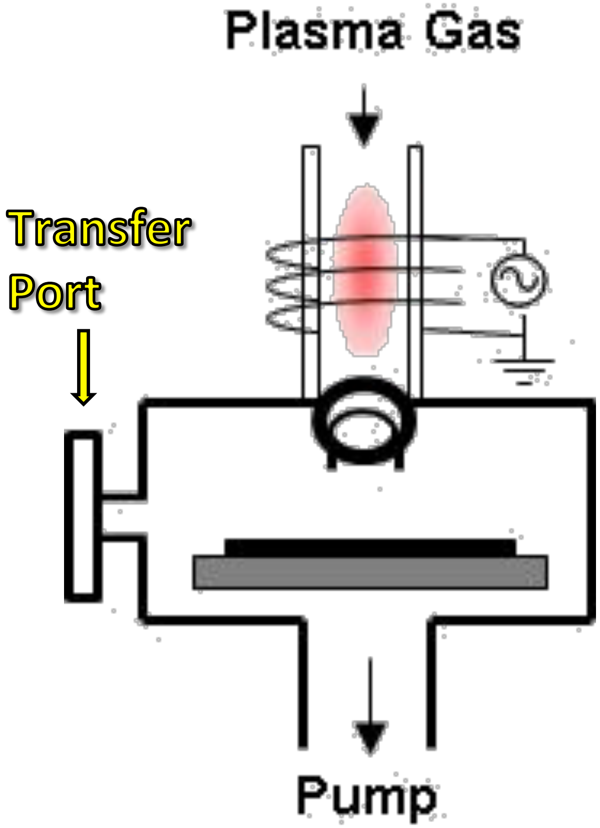
In-situ SE yields atomically resolved information of ALD nucleation

Substrate Transfer

Enabled by Transfer Port integration

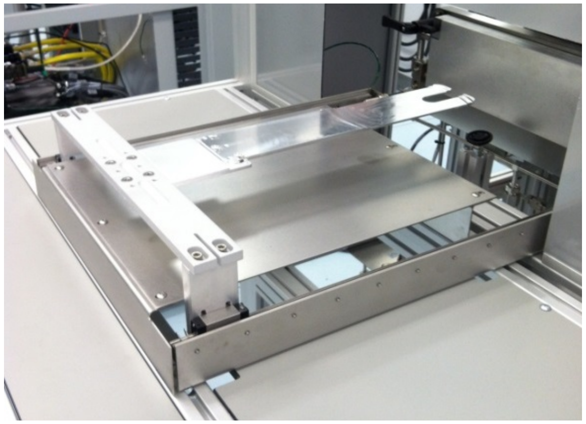


Transfer via automated load-lock reduces contaminants (nitrides), increases throughput



Atmosphere transfer using manual rail assembly

Less forgiving for highly sensitive films



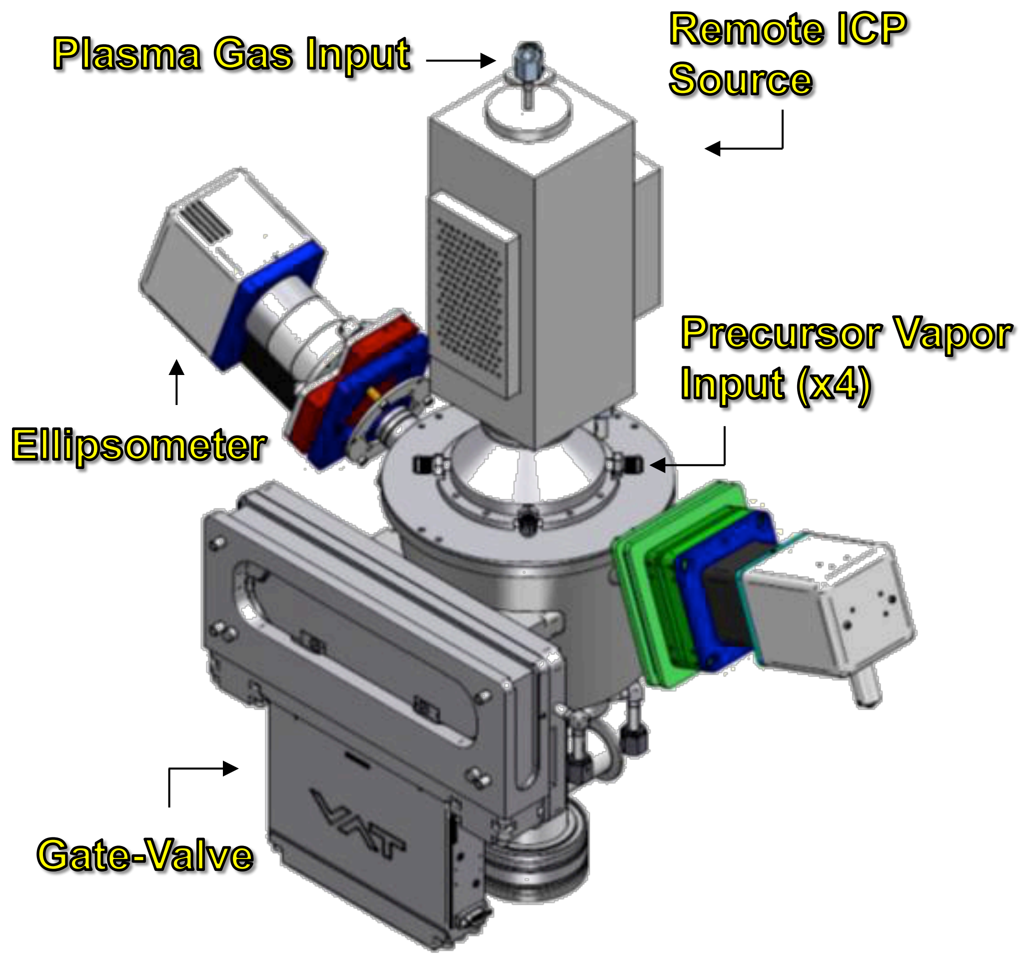
Design Challenges to be considered:

More complex process chamber geometry & increased volume pose significant design challenges

Focus is now on <u>process gas flow</u> considerations

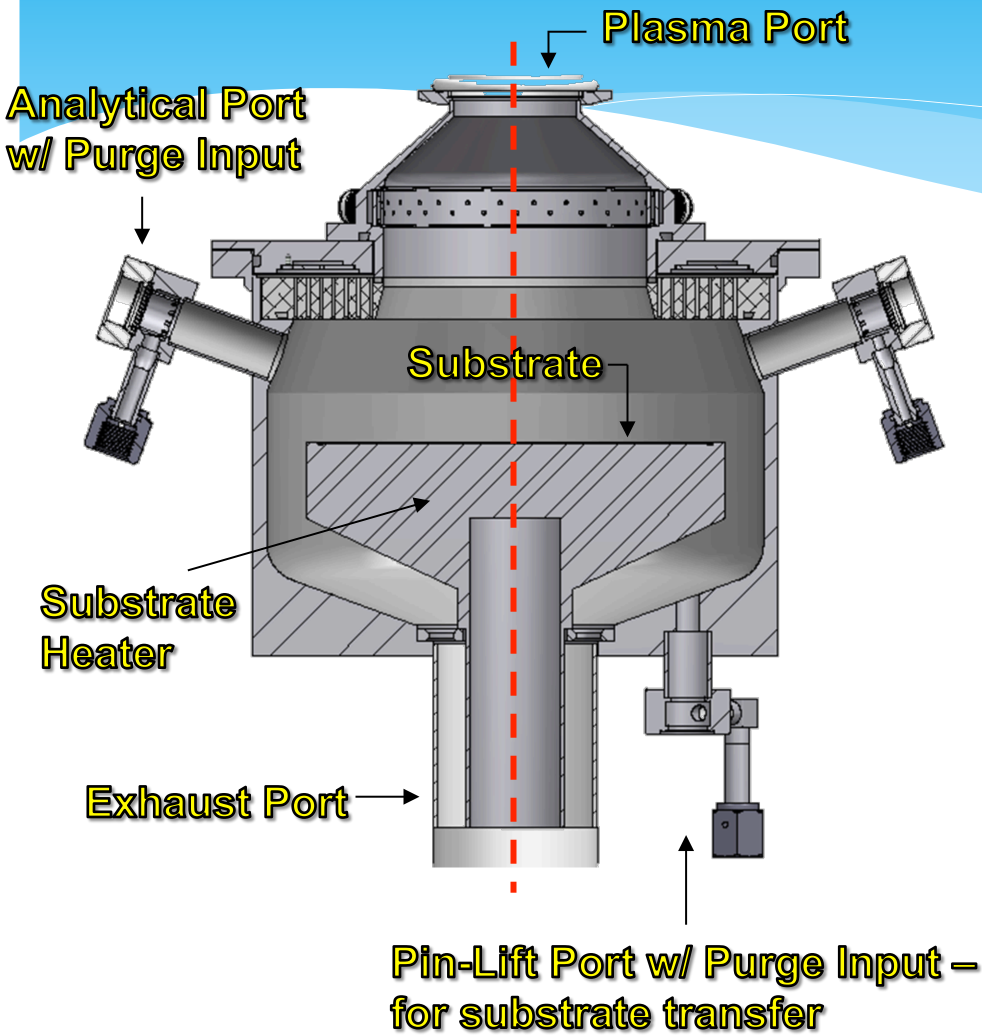
- Precursor & inactive gas distribution for efficient precursor delivery & purging between dose steps
- Uniform precursor delivery without significant waste
- No Precursor trapping – process chamber must be free from pockets (or dead-space volume)
- Inactive gas flow should be viscous & laminar (no recirculation or eddy currents) & must prevent exposure of sensitive surfaces where deposition must be avoided

ALD-150LX Process Chamber Overview



- Up to five precursors introduced through chamber lid assembly – Includes plasma gas & four precursor vapor inputs
- Integrated ellipsometer for in-situ monitoring & control
- Gate-valve (attached to transfer port) provides process chamber to load lock isolation

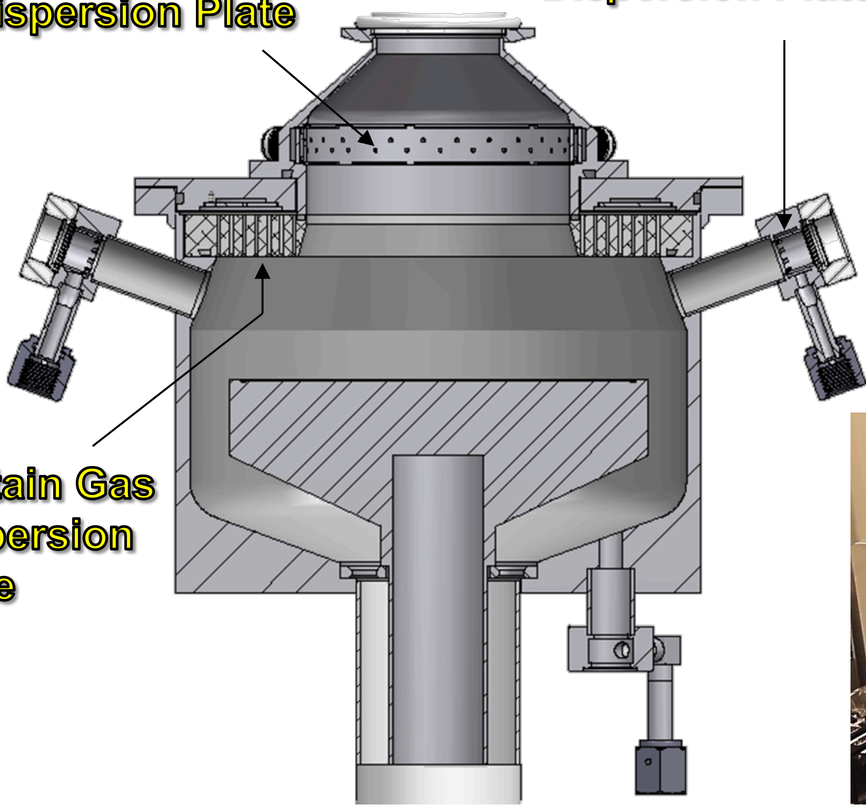
Chamber Cross-section

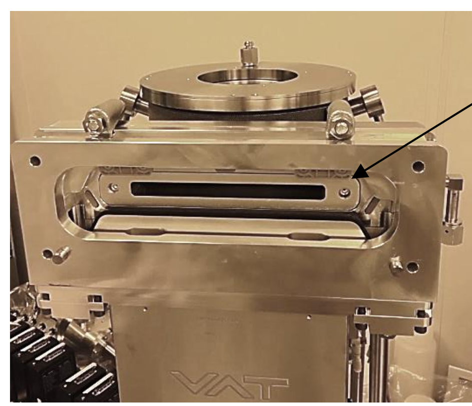


- Perpendicular flow design – Central axis perpendicular to substrate surface
- Centralized plasma & exhaust ports enhance plasma uniformity & distribution
- Relative angle of analytical ports is 70 degrees
- Purge gas provided to ALL ports to eliminate dead space – including transfer port (next slide)

Precursor & Inactive Gas Distribution

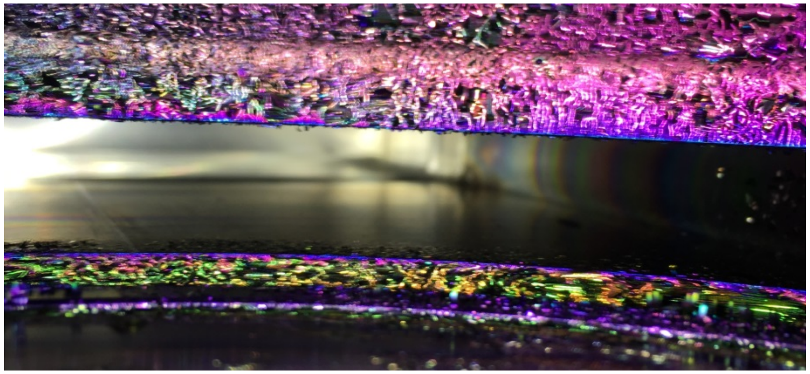
Dispersion plates for precursor, curtain gas, transfer port & analytical ports – promote gas flow uniformity & distribution

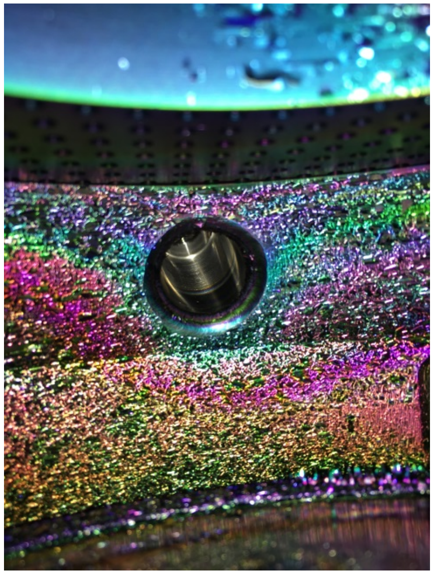




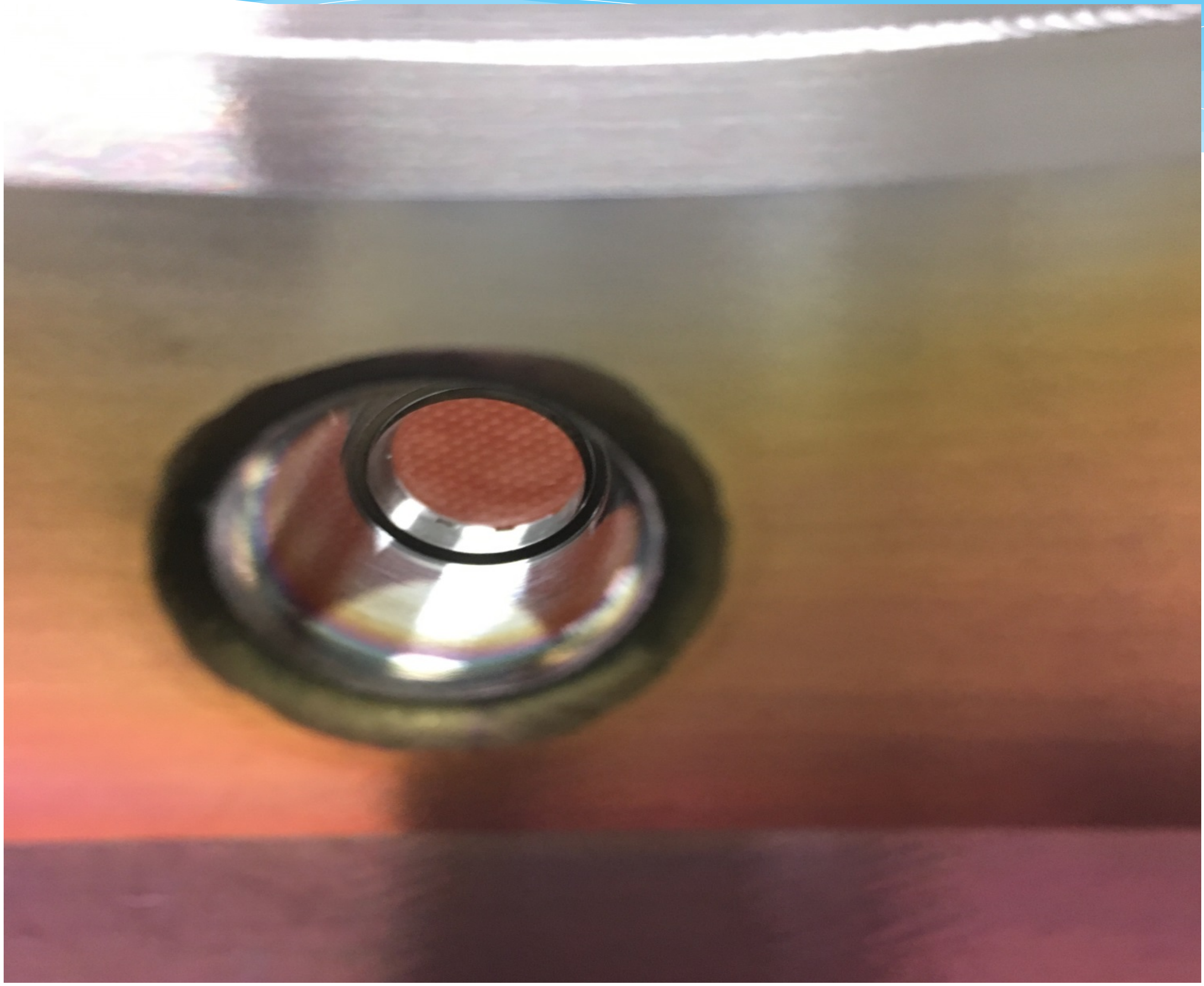
Material Buildup and Purge Ports

2 Years of use



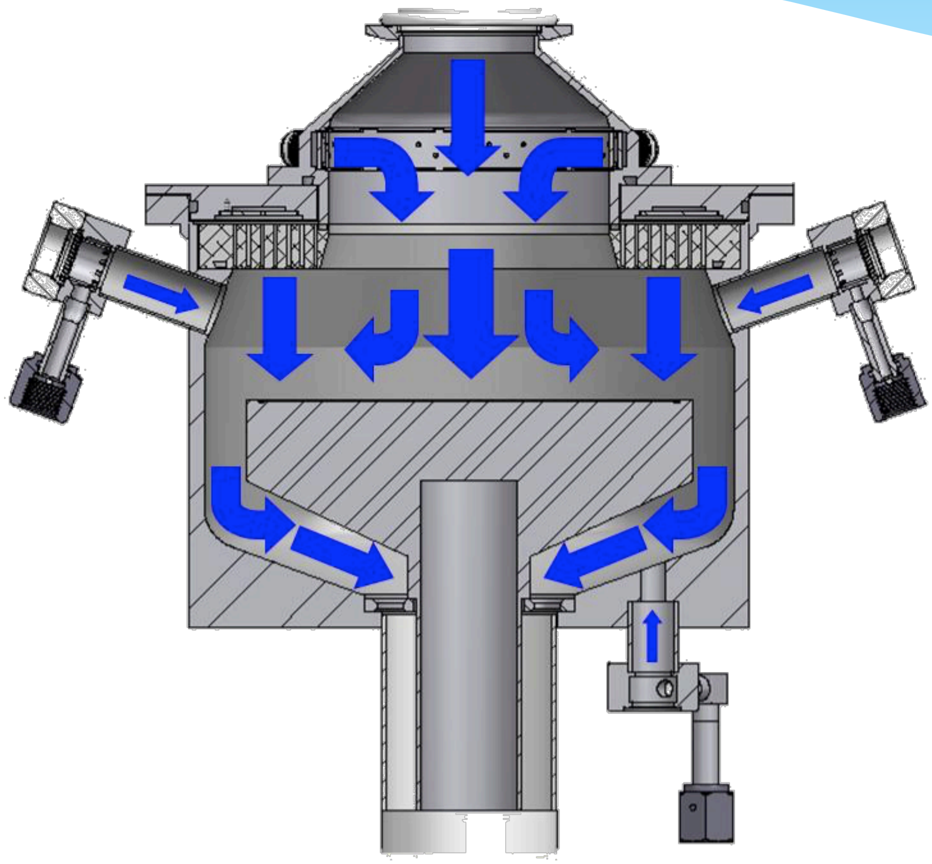


5,000 cycles Al2O3



Gas Flow Dynamics

Inactive gas flow is continuous, viscous & laminar



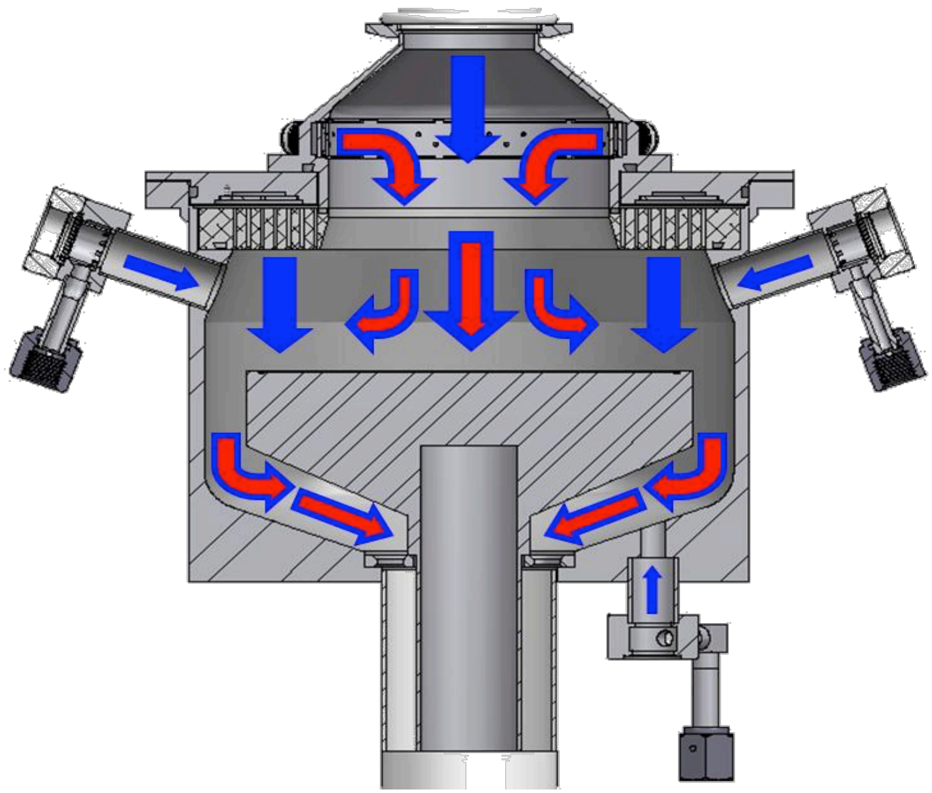
❖ Blue arrows indicate general direction of inactive gas flow

❖ Net direction of flow is perpendicular to substrate surface

❖ Chamber ports are continuously purged to eliminate dead-space volume

Precursor Focusing Technology   US patent number 9,695,510

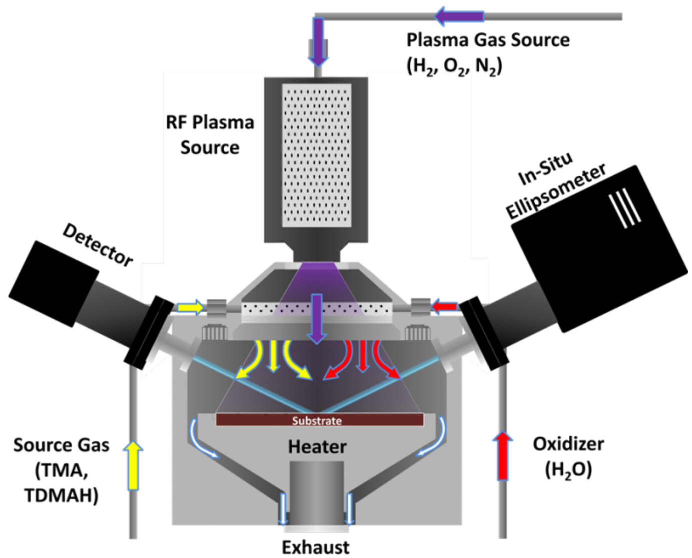
Inactive gas flow distribution focuses precursor onto substrate surface during precursor pulse steps



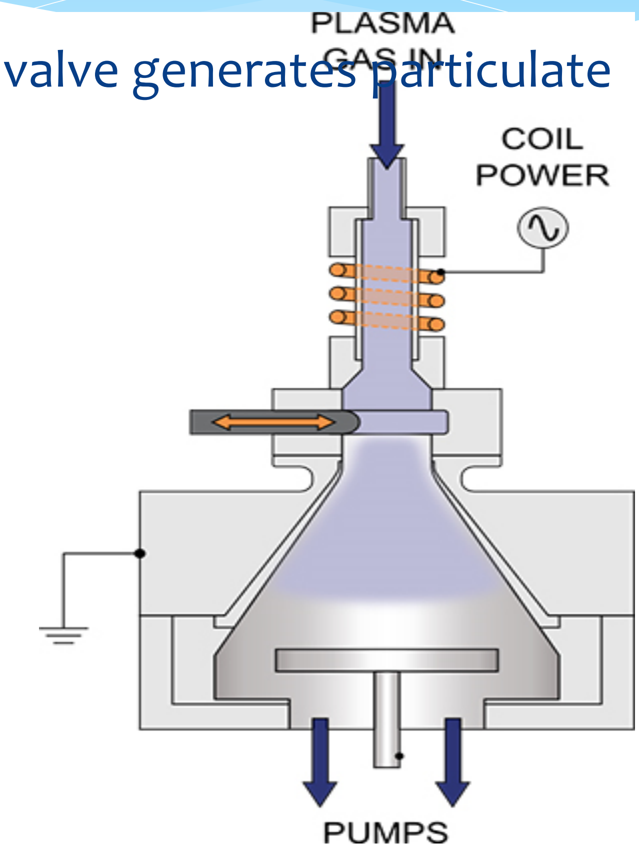
- Blue/Red arrows = mixing of inactive and precursor gas
- Helps protect ports and chamber walls from unwanted precursor exposure – *reduces downtime for chamber cleaning*
- PFT™ (patented) enables efficient precursor utilization & purging
- Eliminates need for gate-valves that generate particles

Remote Plasma & Particulate—Reactor Design Comparison

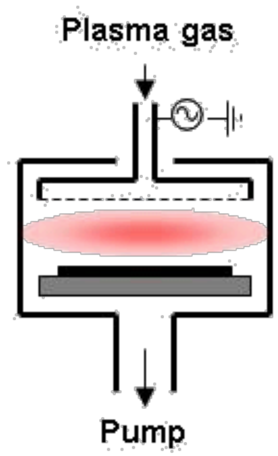
No Valve=reduced particulate



Gate valve generates particulate

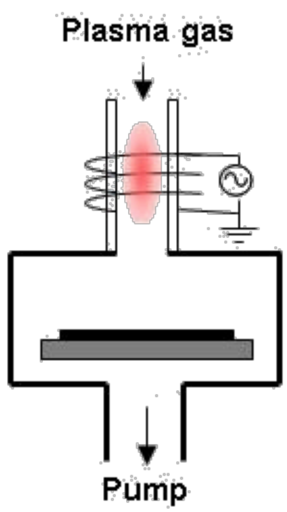


Plasma Enhanced ALD Methods



Direct RF plasma

- Excellent plasma uniformity – but exposes surfaces to high-energy ions (>100 eV)
- Possible sputtering of electrode material



Remote RF plasma

- Uniformity is not as good – but limits surface exposure to low-energy ions only (<20 eV)
- No sputtering of electrode material

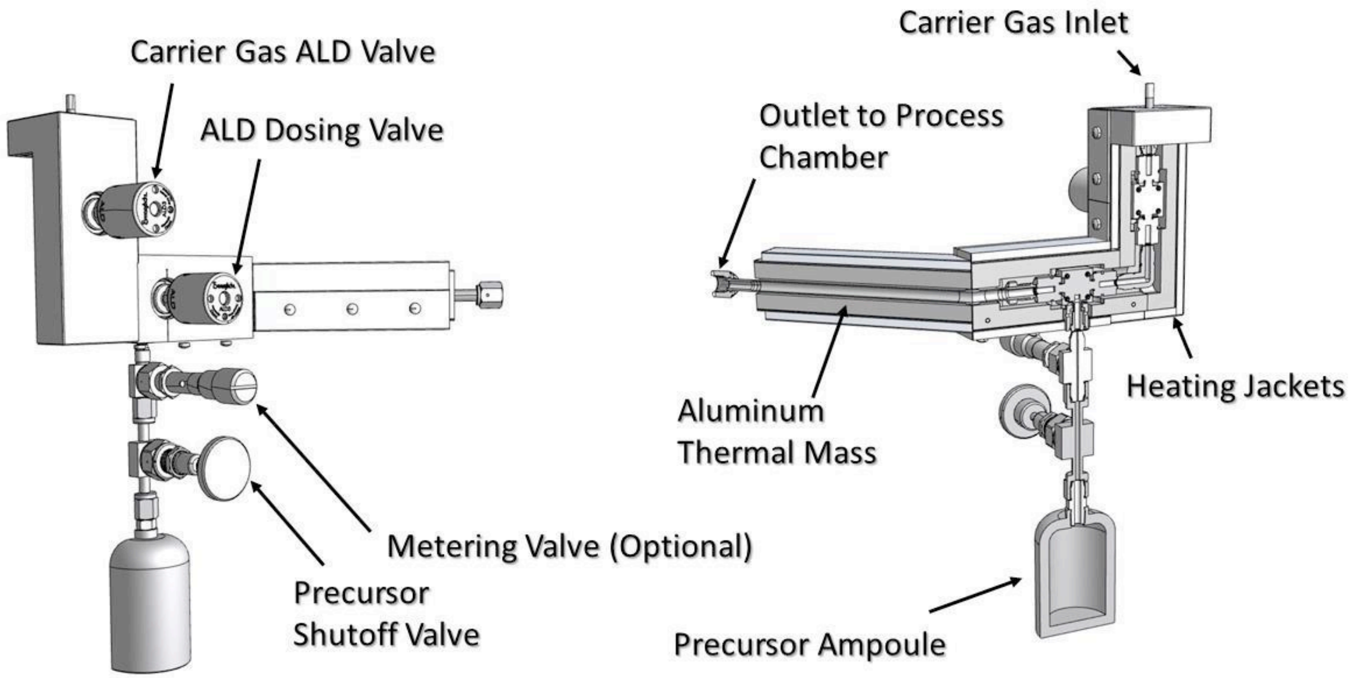
- **Plasma enhanced ALD (PEALD) methods utilize reactive plasma species to promote surface reactions**

- **Benefits of PEALD include:**
  - Lower temperature
  - New pathways for chemical reactions
  - Substrate surface modification (H2 plasma)
  - Chamber cleaning

Thermal Management

- Generally – vapor sources include the following components:
  - Ampoule
  - Valves
  - Line to chamber - SS tubing & VCR components
- Common issues include
  - Precursor vapor condensation (and associated parasitic CVD effects)
    - Uniform heating helps minimize potential for condensation
    - Aluminum cladding and jackets enables temperature non-uniformity of <+/-5% (even across complicated line geometries)

Heating Input Lines



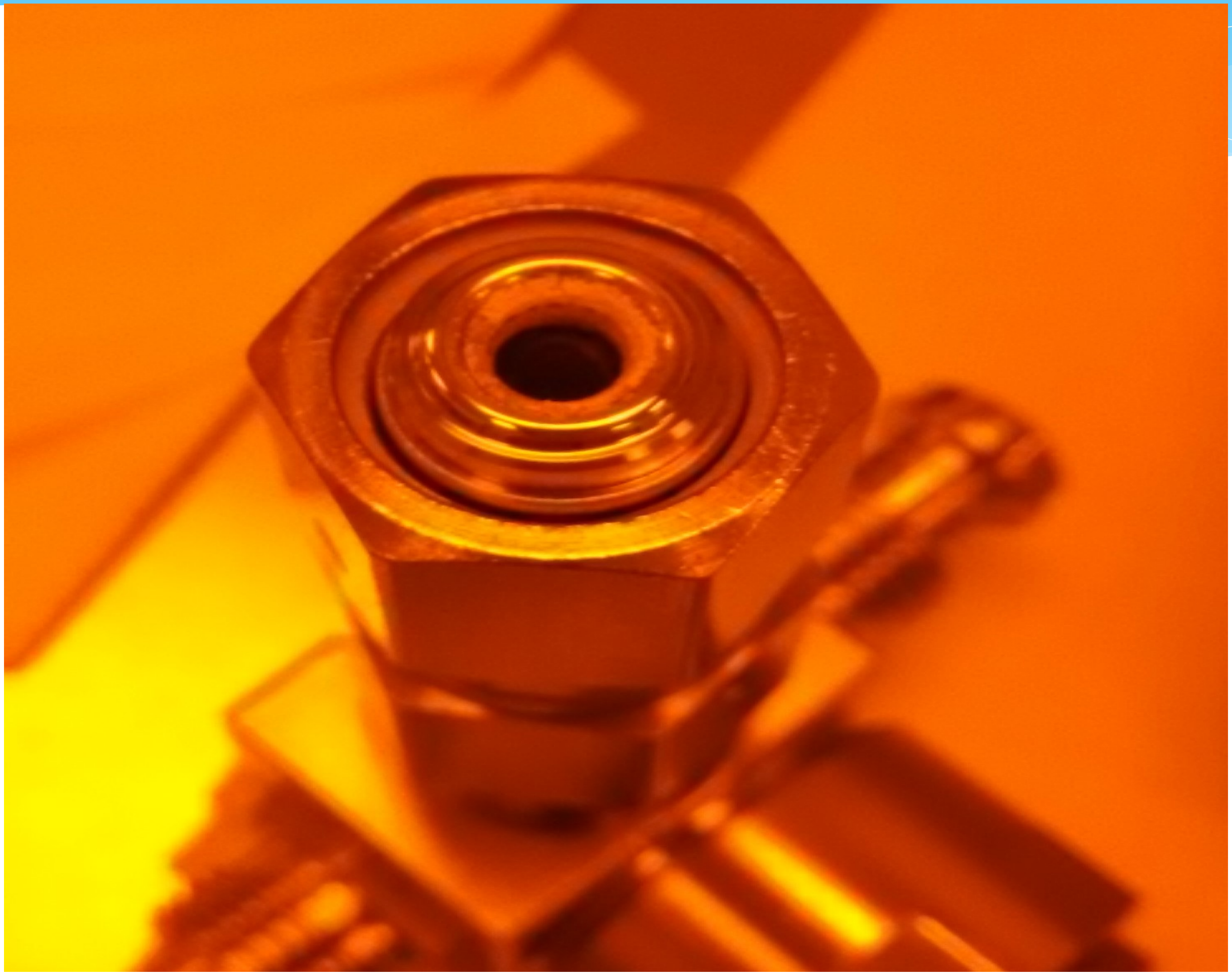
Thermal Management

Corrections to common issues (cont)

- **Multiple heating zones** ensure temperature uniformity – Difficult to maintain uniformity across ampoule, valves & line components with single zone
- **Enables increasing temperature gradient** between source and point of injection – further minimizing potential for precursor condensation

- **Material buildup in valve/line components**
  - Eliminate buildup by having **separate inputs** for reactants – e.g., separate valves/lines for metal organic and oxidant sources
  - Eliminates the possibility for ALD/CVD on surfaces of delivery components (valves, lines, VCR connections)

Line Condensation and Deposition on Common Line



Vacuum Management

* Quite often overlooked
* Load locks operate at 10-7 Torr
* Reaction chambers operate at approximately 1 Torr

Vacuum

* High Quality Transition Metals (TaN,TiN) require UHP conditions to eliminate O2 and other contaminants
* KJLC has developed IP centered around UHP reactor and plasma source design
* Yielding a 3-4 order or magnitude reduction in O2 component over standard designs

Summary

* ALD is both simple and complex
* One size does not fit all (i.e. nitrides,oxides, metals)
* Tool design determines film quality and tool uptime
* Precursor delivery, load lock, plasma, in-situ ellipsometry and thermal management are key design considerations.

Acknowledgments

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Thank You