NCCAVS 2018

TOOL DESIGN CONSIDERATIONS FOR ADVANCED ATOMIC LAYER DEPOSITION

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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. 2\textsuperscript{nd} 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

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

- Slow
- Material limitations
- Parasitic reactions can occur
Conformal

$Al_2O_3$

10 μm 30.0 kV 9.15E3 9936/00
Initial stages of Ru PEALD using RuO₄ 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
Al₂O₃ 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 process gas flow 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

- 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

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
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)

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Heating Input Lines

- Carrier Gas ALD Valve
- ALD Dosing Valve
- Metering Valve (Optional)
- Precursor Shutoff Valve
- Precursor Ampoule
- Carrier Gas Inlet
- Outlet to Process Chamber
- Aluminum Thermal Mass
- Heating Jackets
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
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.
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

- Dr. Bangzhi Liu – Penn State University Nanofab
- Dr. Bruce Rayner, Noel O’Toole - Kurt Lesker Company
Thank You