Atomic Layer Deposition for Nano-Manufacturing

June 24, 2010

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NanoTech

Outline

- About Cambridge NanoTech
- Atomic Layer Deposition (ALD)
- Selected Applications
- Manufacturing Considerations
- ALD Reactors
- Summary

About Cambridge NanoTech

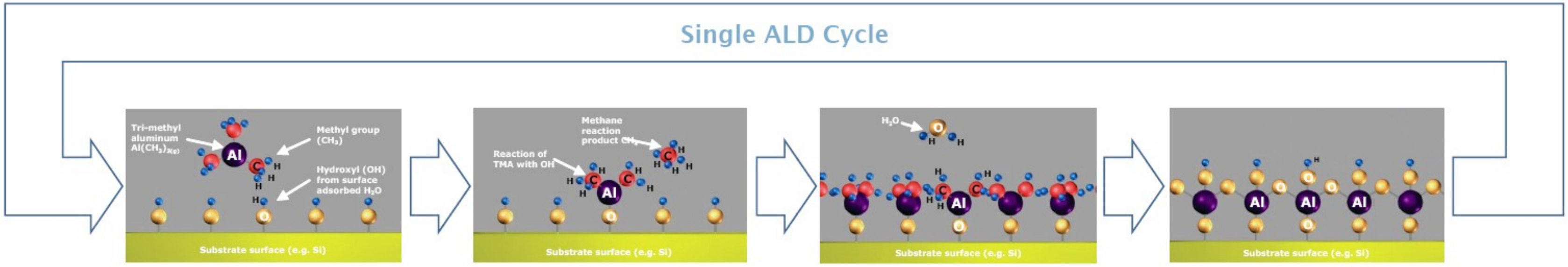
- Founded in 2003 by Dr. Jill Becker
- Located in Cambridge, MA
- Grew directly out of Gordon Lab at Harvard University
- Dedicated to advancing the science and technology of ALD
- Multiple ALD product lines serving many applications and industries
- Rapid response to custom applications and projects
- Full staff of Ph.D. research scientists
- Strategic partnerships deliver complete ALD solution

SIGMA-ALDRICH STREM CHEMICALS, INC. MBRAUN Swagelok

The ALD Cycle

- A single ALD cycle consists of the following steps:
  - 1) Exposure of the first precursor
  - 2) Purge or evacuation to remove by-products
  - 3) Exposure of the second precursor
  - 4) Purge or evacuation of the reaction chamber

- In the example below, precursors Trimethylaluminum (TMA) and H_2O are alternately pulsed to deposit an Aluminum Oxide (Al_2O_3) film



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ALD Deposits Thin Inorganic Films

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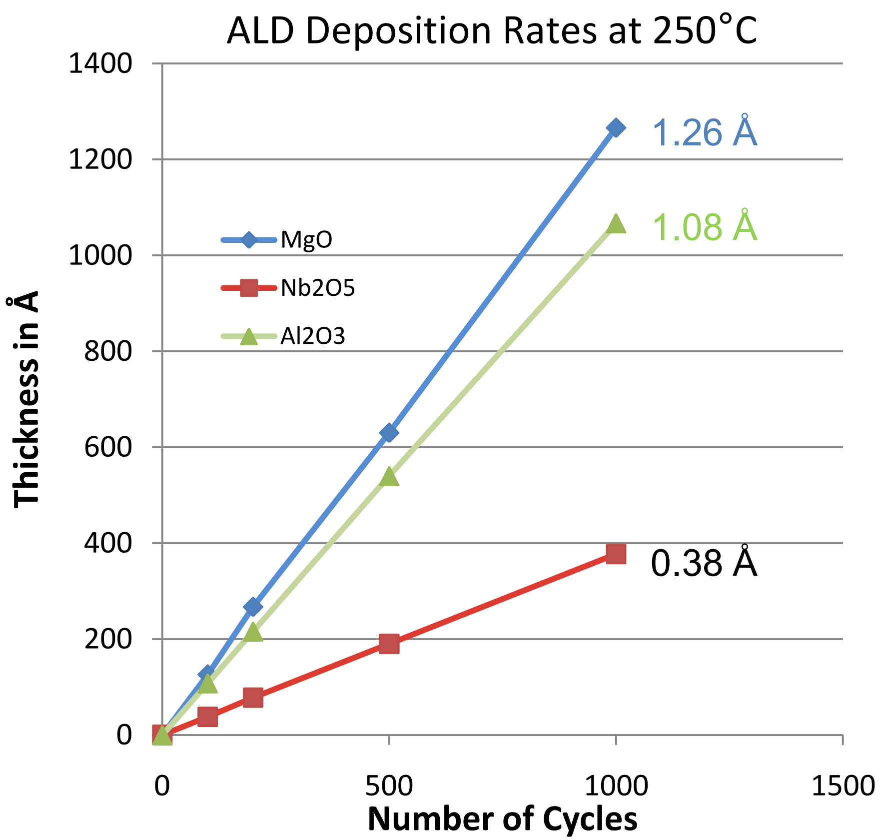
ALD Films

- Films deposited with digital control of thickness; “built layer-by layer”
- Each film has a characteristic growth rate for a particular temperature



Oxides

Al_2O_3, HfO_2, La_2O_3, SiO_2, TiO_2, ZnO, ZrO_2, Ta_2O_5, In_2O_3, SnO_2, ITO, FeO_x, NiO_2, MnO_x, Nb_2O_5, MgO, Er_2O_3

Nitrides

WN, Hf_3N_4, Zr_3N_4, AlN, TiN, TaN, NbN_x

Metals

Ru, Pt, W, Ni, Co

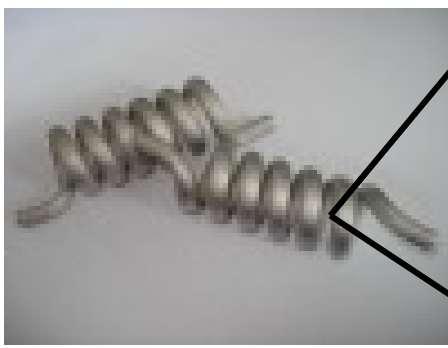
Benefits of ALD

100 nm Al_2O_3 coating on Si wafer

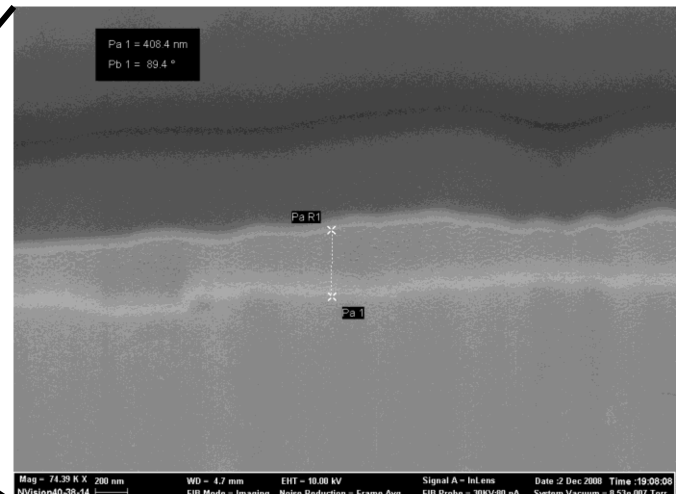
- **Perfect films**
  - Digital control of film thickness
  - Excellent repeatability
  - 100% film density
  - Amorphous or crystalline films
  - Ultra thin films: <10nm possible
- **Conformal Coating**
  - Perfect 3D conformality
  - Ultra high aspect ratio (>2,000:1)
  - Large area thickness uniformity
  - Atomically flat and smooth coating
- **Challenging Substrates**
  - Gentle deposition process for sensitive substrates
  - Low temperature and low stress
  - Excellent adhesion
  - Coats challenging substrates – even teflon

Successful Coating of Irregular Shapes

- Conformal coating of irregular topographies
- ALD film will deposit where ever precursor can infiltrate, without shadowing or line-of-sight issues



Coiled stainless steel tubing



Protective layer of Carbon

Conformal Ru coating

Stainless Steel

FIB Cross-section of interior coated with ALD deposited Ru

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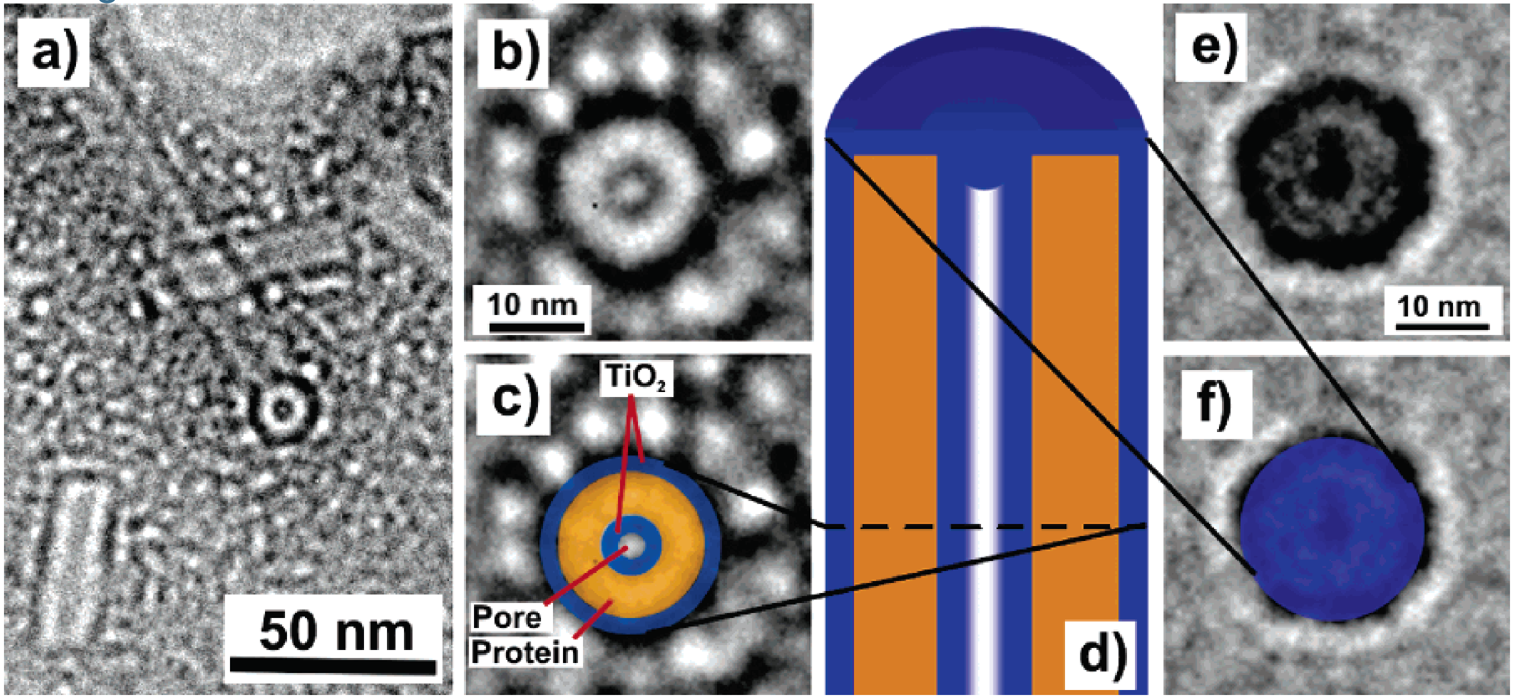
ALD on Biological Templates

- Biological macromolecules enable fabrication of 3-D semiconducting / metallic/ insulative nanostructures

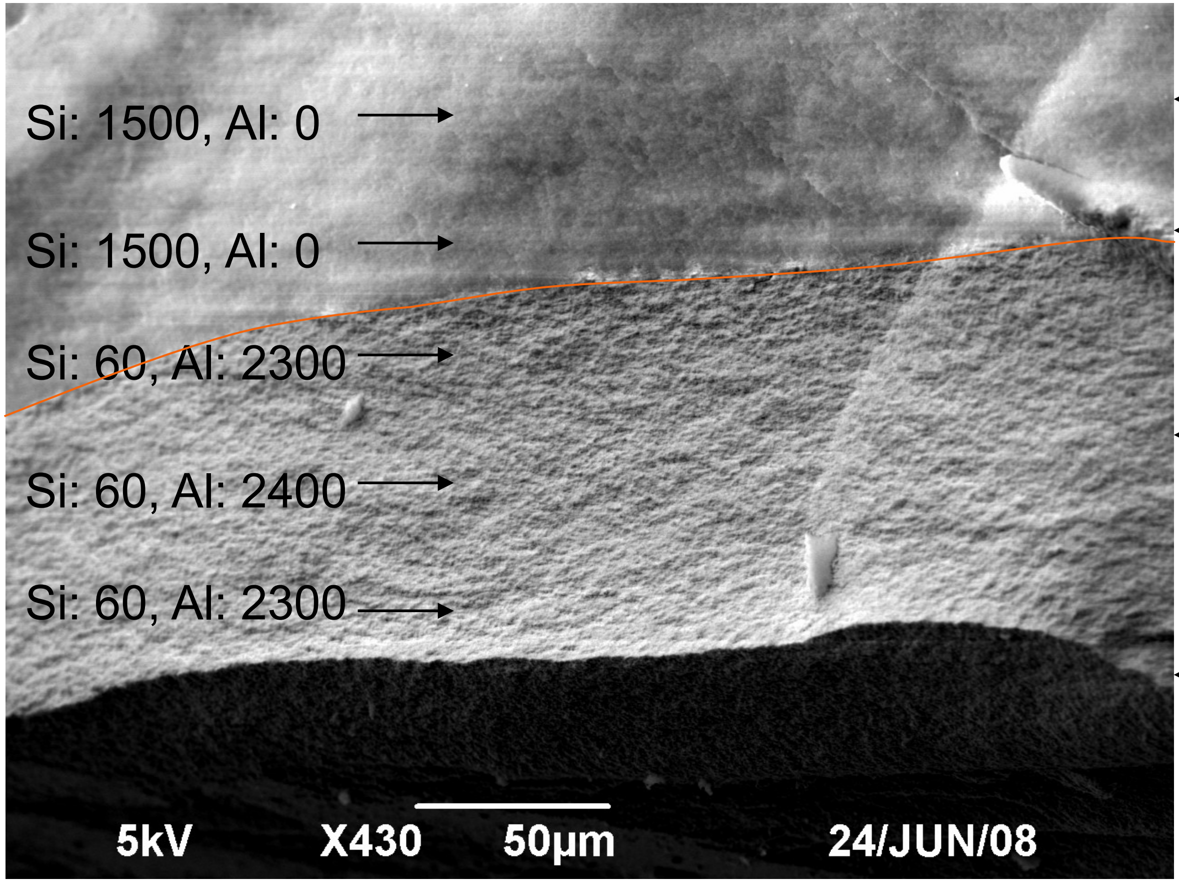
Deposition of TiO_2 inside and around tubular shaped tobacco mosaic virus length 300 nm, OD 18 nm, ID 4 nm. Grown < 80°C



Courtesy of M. Knez, MPI Halle

Al_2O_3 Infiltration – Silica Aerogel

- Successful conformal coating of 2000:1 aspect ratio inside porous aerogel



Bulk SiO_2 with no Al

End of Al_2O_3 layer

Al_2O_3 coated foam
With very little Si

Foam surface

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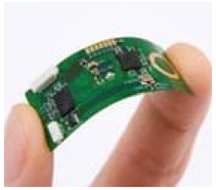
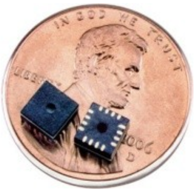
ALD Applications

Optical
Antireflection
Optical filters
OLED layers
Photonic crystals
Transparent conductors
Electroluminescence
Solar cells
Lasers
Integrated optics
UV blocking
Colored coatings



Semi / Nanoelectronics
Flexible electronics
Gate dielectrics
Gate electrodes
Metal Interconnects
Diffusion barriers
DRAM
Multilayer-capacitors
Read heads

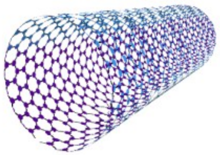


MEMS
Etch resistance
Hydrophobic / antistiction

Chemical
Catalysis
Fuel cells

Other applications
Internal tube liners
Nano-glue
Biocompatibility
Magnetic

Wear resistant
Blade edges
Molds and dies
Solid lubricants
Anti corrosion



Nanostructures
Inside pores
Nanotubes
Around particles
AFM tips
Graphene

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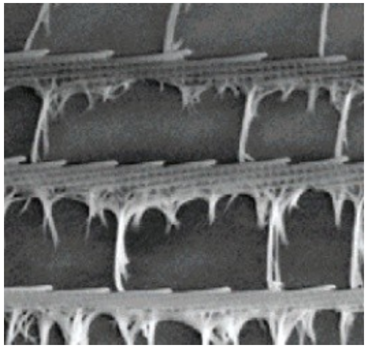
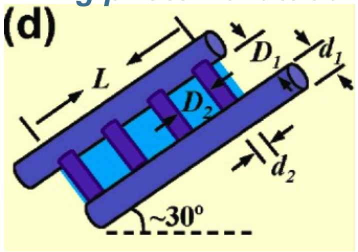
Low Temperature ALD

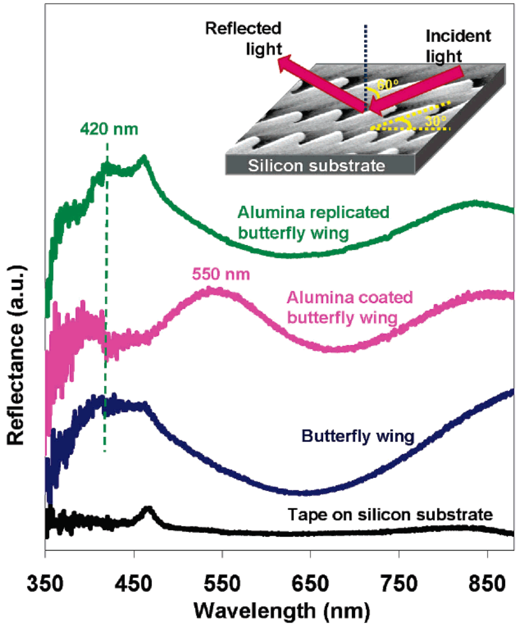
- Films deposited < 150°C: Al_2O_3, HfO_2, SiO_2, TiO_2, ZnO, ZrO_2, Ta_2O_5, SnO_2, Nb_2O_5, MgO
- Ideal for merging organics with inorganics
- Compatible with photoresist, plastics, biomaterials

***Morpho Peleides* butterfly**



Wing photonic lattice

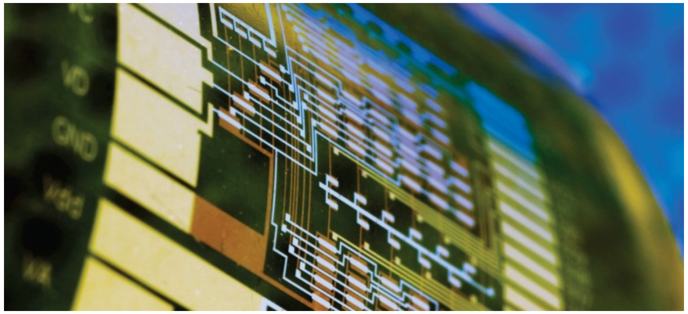


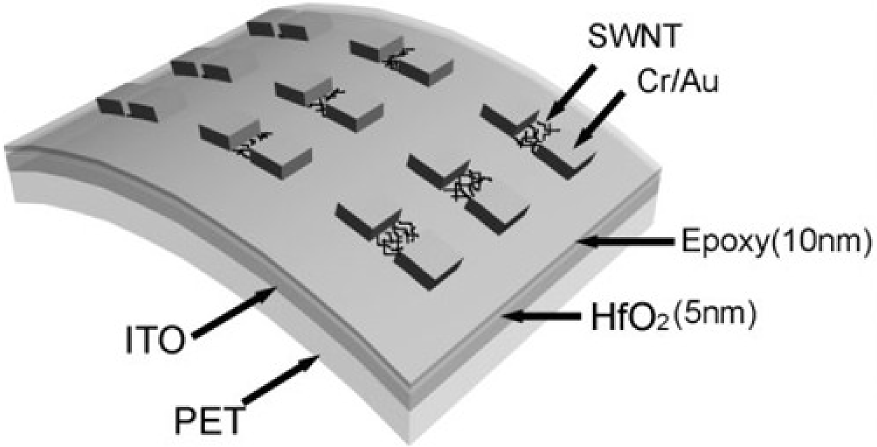


Huang J. Y. *Nano Letters.* **2006**, 6, 2325

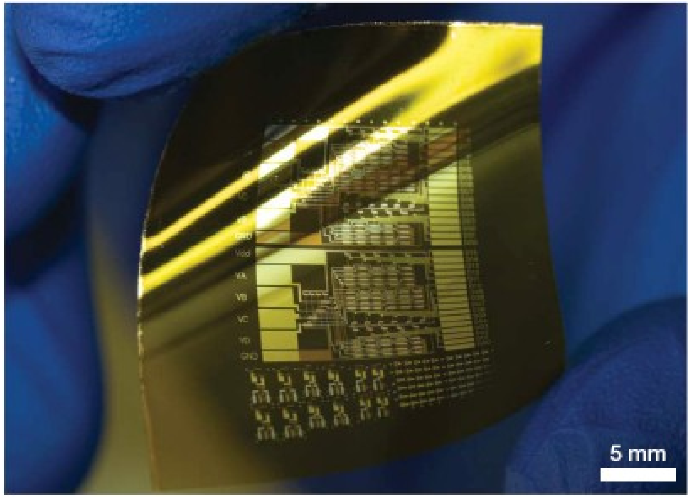
ALD for Flexible Electronics

- High quality HfO_2 gate dielectric, deposited at 100°C
- Low stress film - flexible





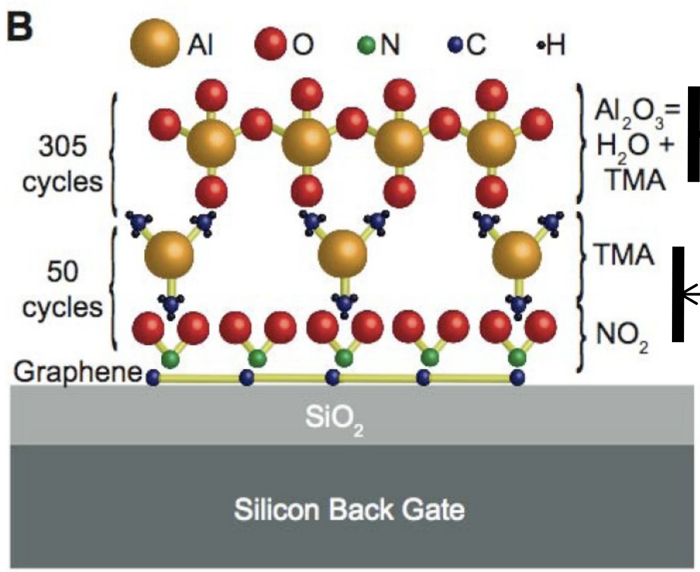
Advanced Functional Materials, ***2006***, *16*, *2355-2362.*
Nature, **2008**, *454*, 495-500.



large capacitance (up to ca. 330 nF cm^{-2}), and low leakage current (ca. 10^{-8} A cm^{-2})

Functionalizing Graphene

- To make useful devices – need to control carriers
- Need to first functionalize the Graphene surface.
- Requirements:
  - Non interacting layer with Graphene and yet a good material for the growth of the gate dielectric (Al_2O_3)



Done at 225°C in an ALD reactor (gate dielectric growth)

Done at room temperature in an ALD reactor (functionalization step)

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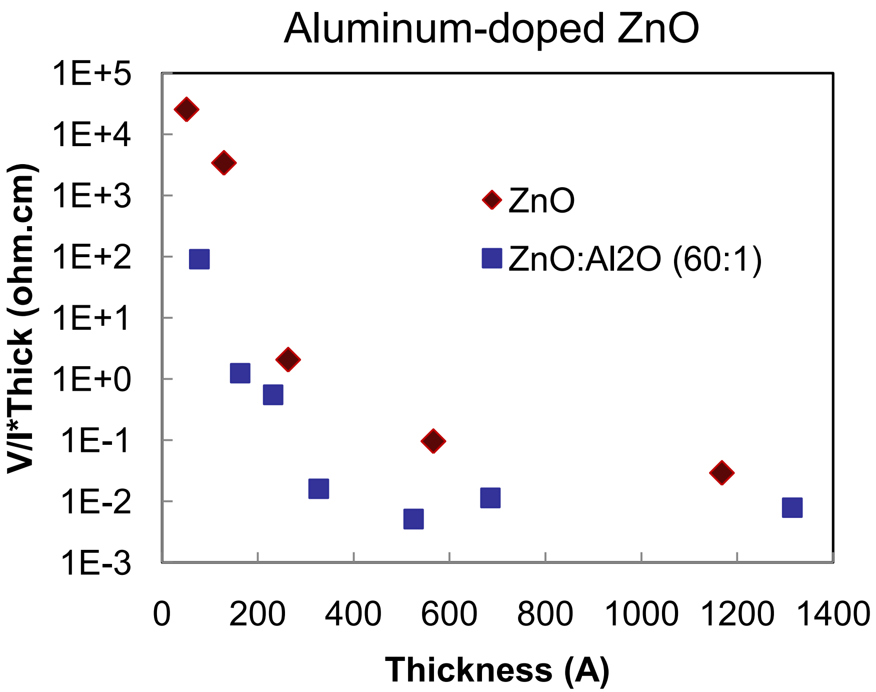
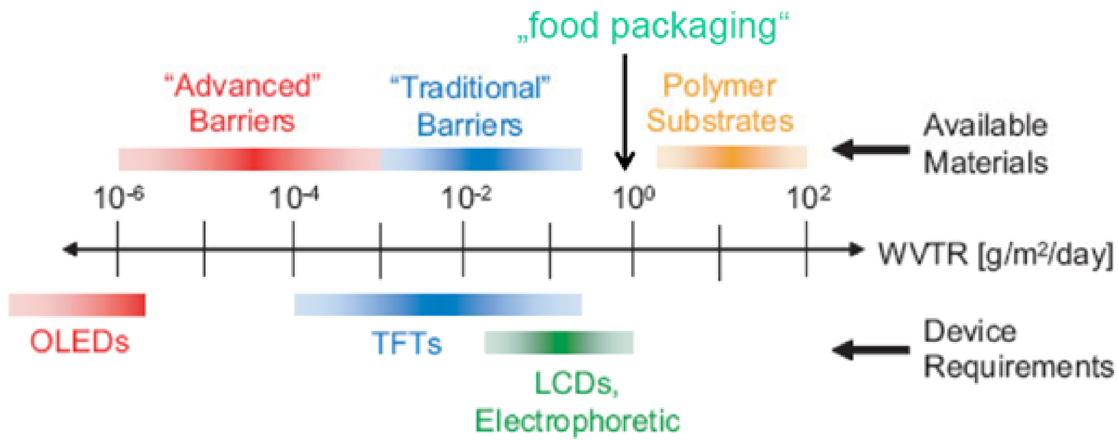
ALD for Transparent Conducting Oxides

- ALD deposited Indium-Tin Oxide (ITO) at 250°C
  - Resistivity: 2 – 30 X 10^{-4} Ω.cm, Thickness >200 Å
- Sensitive substrates require low process temperatures <120°C



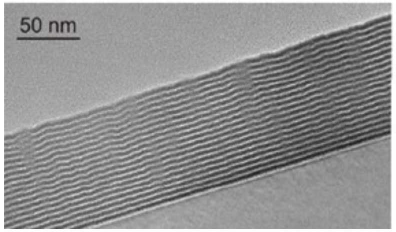
- Al_2O_3-doped ZnO_2 resistivity:
  - 2.8 X 10^{-3} Ω·cm at 120°C
- Optical transparency, bandgap tunable without consequence on resistivity

ALD for Moisture Barriers



- Improved performance water and oxygen barrier by using nanolaminate layers of 5nm Al_2O_3 and ZrO_2
- Water Vapor Transmission Rate (WVTR) $<10^{-6}$ g/m^2 day demonstrated

Advanced Materials **2009**, *21*, 1845-1849



ALD Process Considerations

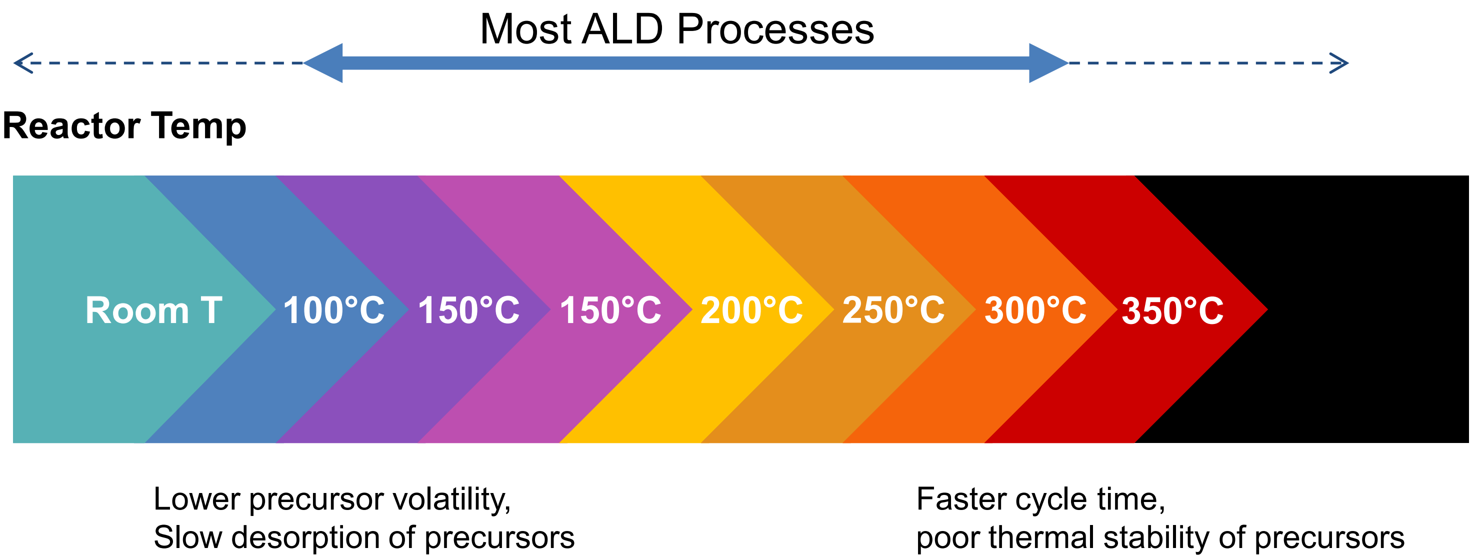
- Not all materials/processes are available for deposition by ALD or are appropriate for high-volume manufacturing
- Why?

Precursors

- Most precursors are air-sensitive: requires inert atmosphere or vacuum
  - Appropriate precursor chemistry
    - Must be thermally stable
    - Volatile / Reactive
    - Commercially produced and cost-effective
    - Compatibility with substrate / manufacturing

ALD Reaction Temperatures

- ALD is a chemistry driven process
- Based on precursor volatility/reactivity



ALD Process Considerations

Process Pressure

- ALD is generally pressure insensitive: can be performed at atmosphere
- Typical ALD reactors operate between 1-500mTorr
- Lower volatility precursors require lower process pressures

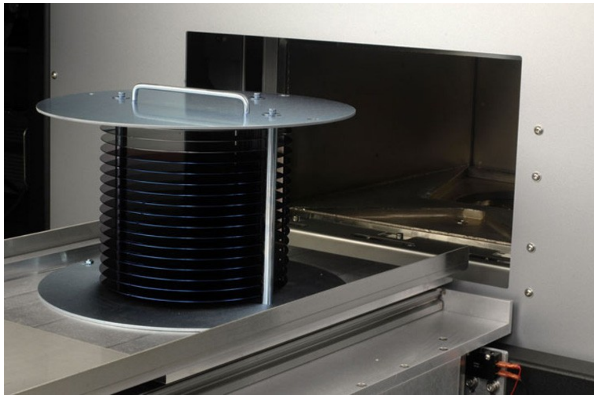
Hardware Design

- Sizing of vacuum pump to clear byproducts – cycle times (sub 1 second possible)
- Precursor introduction / distribution to ensure saturation

Manufacturing Considerations

Process Times

- Typical process time 1-30 seconds per cycle
- 20-500Å of material typically deposited
- "Batch" reactor will accommodate one hundred 200mm wafers
- Less than 2 hours of reactor time for 250Å



Batch cassette for 300mm wafers

ALD for Manufacturing

- Integration of ALD hardware into process line
  - Glovebox, clustering, robot loading, batch cassette integration

In-line Systems

- Air exclusion; reduction of process time (eliminates pump down time)
- Large flexible substrates (displays, solar, roll-to-roll)

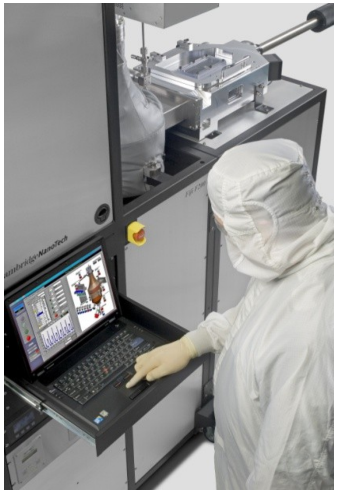
Product Portfolio

Cambridge NanoTech ALD systems are engineered for a wide variety of applications from research to high-volume manufacturing.

Savannah

Compact, cost-effective system for research

Fiji



Plasma system for research

Phoenix

Batch manufacturing system

Tahiti

Large area manufacturing system

Research → Production

Time to Production

Case Study: MEMS technology

Application: two layers, one to prevent stiction of MEMS device and another to prevent degradation via atmosphere (water)

R&D: - "Savannah" 200mm reactor

- Tested ALD layers for anti-stiction on R&D samples
- found ALD layers solved stiction issue, also acts as enhanced H_2O barrier

200mm Savannah

Phoenix Batch System

Pilot Scale: - "Phoenix" Batch System
-Scaled ALD deposition conditions from R&D reactor to "batch" pilot machine for qualification testing in less than one week
-Five 370 X 470mm glass plates per batch
-Identical film properties to R&D reactor

Tahiti – large format system

Manufacturing: "Tahiti" Production System

- Designed, built and qualified Production system in under 6 months
- Scaled ALD depositions conditions to manufacturing POR **in 10 runs**
- **Identical film properties to R&D and Pilot Scale batch reactor**
- Currently in production for commercial product; 920 X 730 mm plate

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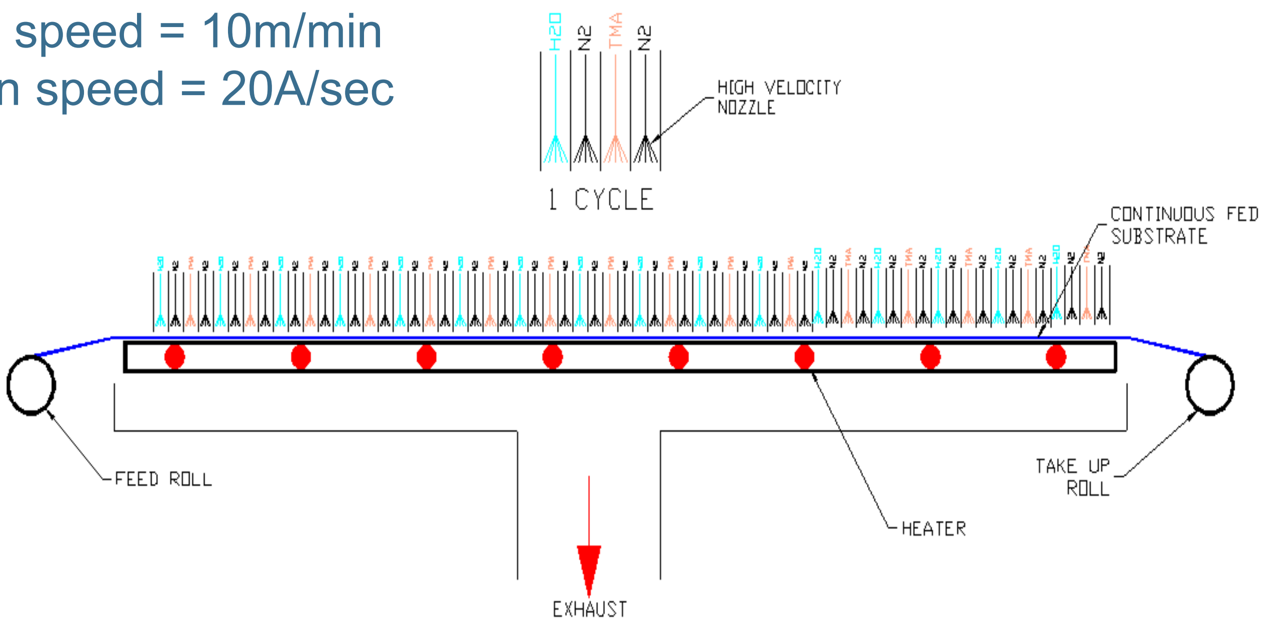
Roll-to-Roll ALD Processing

- Funding for R2R project approved by consortium of Flexible Electronics companies. Delivery slated for 2012

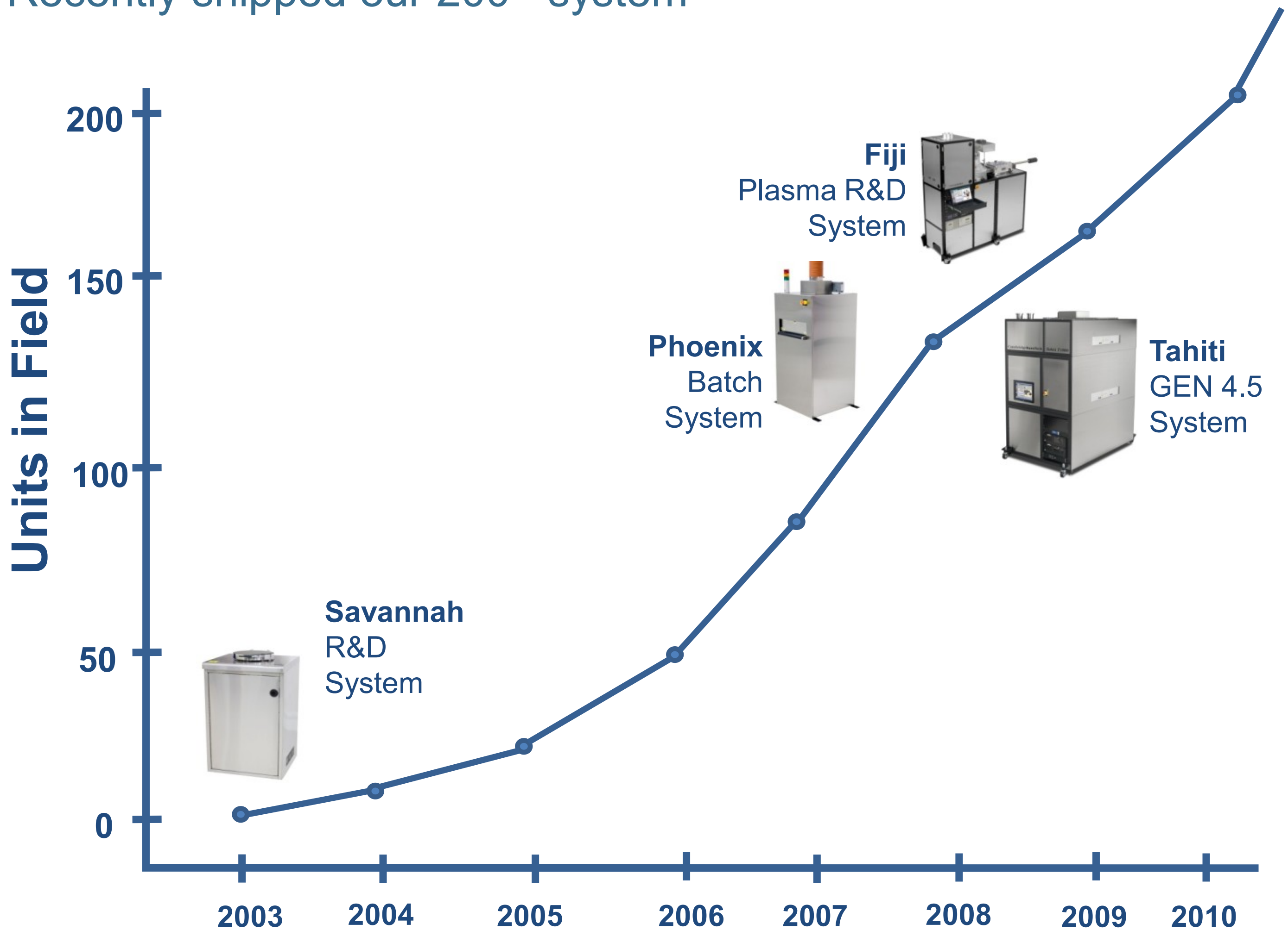
Project Goals

- Sub-second cycle time
- Ability to handle web sizes >1m
- Substrate speed = 10m/min
- Deposition speed = 20A/sec



Industry Leader: Installed ALD Systems

- Recently shipped our 200th system



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ALD Experts

Savannah S300

- Cambridge NanoTech offers a wide variety of ALD tools:
  - Research
  - Plasma
  - Batch manufacturing
  - Large area manufacturing
- Coating Services for ALD film evaluation
- ALD Consulting Services
- Partnerships with industry leaders to provide our customers with a complete ALD solution