# Atomic Scale Processing

ALD, ALE & CVD process solutions

# Atomic Scale Processing

## Driving innovation at the atomic scale

Atomic scale processing means wafer-scale processing with control at the atomic scale. This atomic-level control extends to deposition of thin films, removal or etching of material, and growth of 1D and 2D materials.

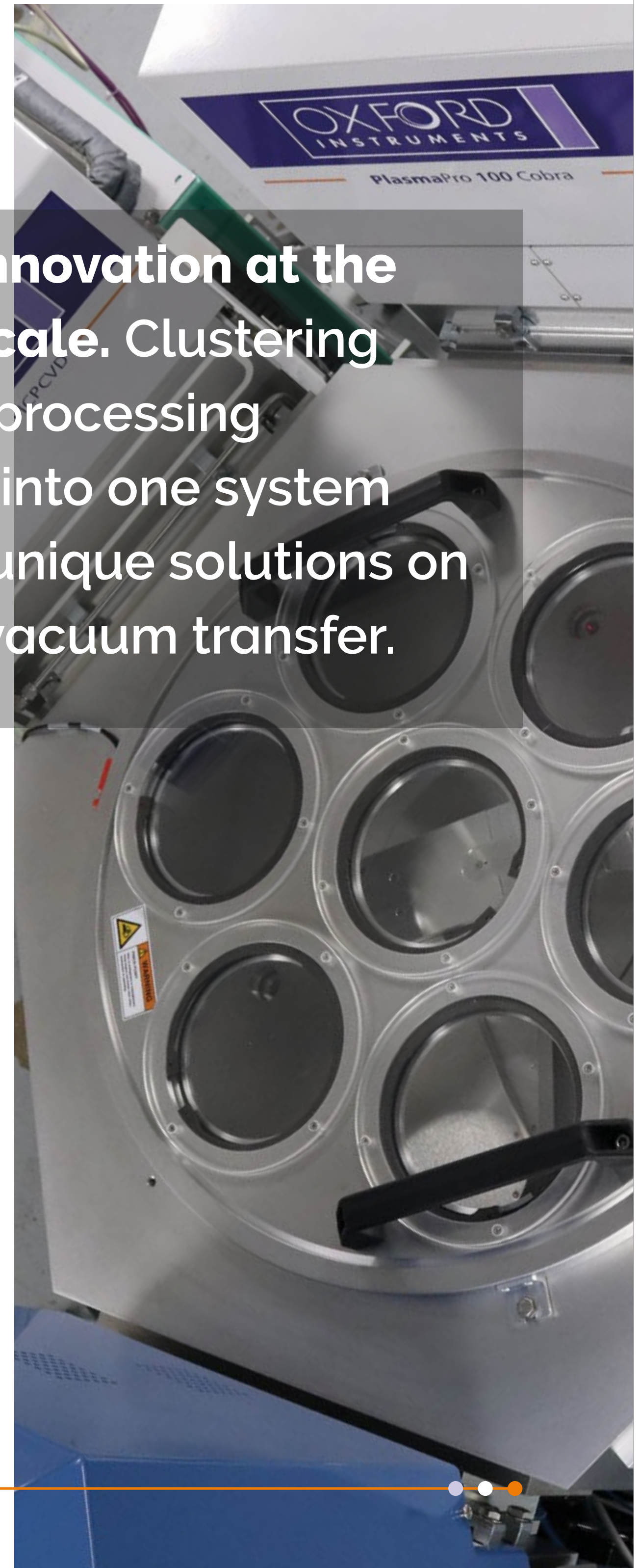
**Fundamental Research and Development Toolkit – Clusterable Atomic Scale Processing Technology**

- Atomic Layer Deposition (ALD) of dielectrics & conductive materials with low damage
- Atomic Layer Etch (ALE) of Silicon, GaN & 2D materials
- 1D & 2D materials growth - Chemical Vapour Deposition (CVD) & ALD of atomically thin structures

**Example applications**

- GaN, SiC and next generation power devices
- Conformal dielectric coatings for high-*K* gates, photonics, microfluidics, MEMS
- Graphene and 2D materials
- Biocompatible layers for medical devices
- Passivation layers for BioMEMS, OLEDs, solar cells
- Electron and hole transport layers in perovskite solar cells
- High aspect ratio diffusion barriers for Cu interconnects
- Storage capacitor dielectrics

**Driving innovation at the atomic scale.** Clustering multiple processing modules into one system enables unique solutions on a single vacuum transfer.






# Atomic Layer Deposition (ALD)

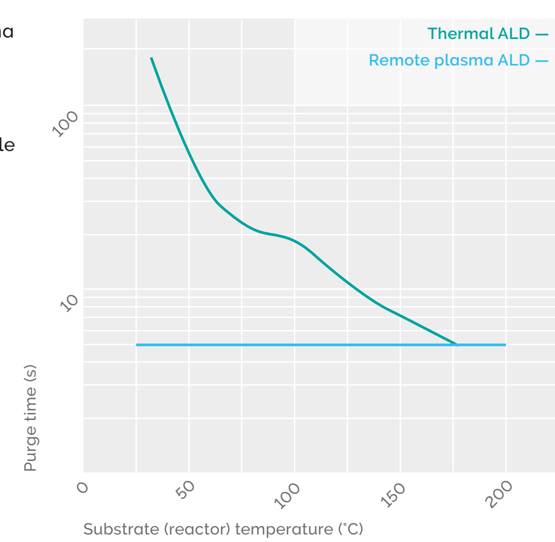
ALD offers precisely controlled ultra-thin films for advanced applications on the nanometre scale.

## Oxford Instruments' ALD equipment offers unique capability by combining remote plasma ALD processes with thermal ALD.

The remote plasma option allows for the widest possible choice of precursor chemistry with enhanced film quality.

- Plasma enables low-temperature ALD processes and the remote source maintains low plasma damage
- Eliminates the need for water as a precursor, reducing purge times between ALD cycles
- Higher quality films through improved removal of impurities, leading to lower resistivity conducting layers and higher density insulators

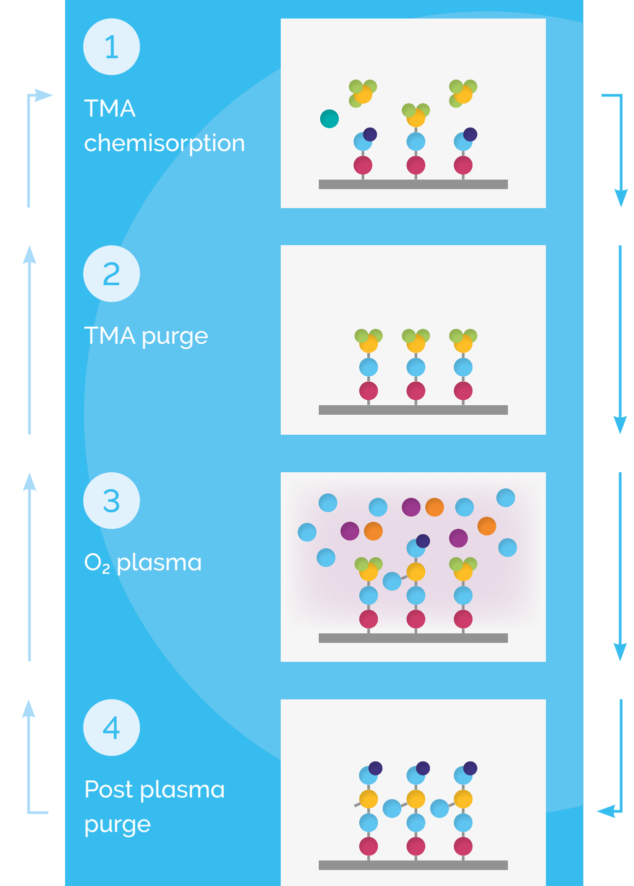
The reactivity of plasma and volatility of the species used allows for short purge times, even at very low sample temperatures.




## ALD cycle

**—for $Al_2O_3$ deposited using TMA and $O_2$ plasma**

**Key:** O, Si, Al, H, $CH_3$, $CO_2$, $H_2O$, $CH_4$

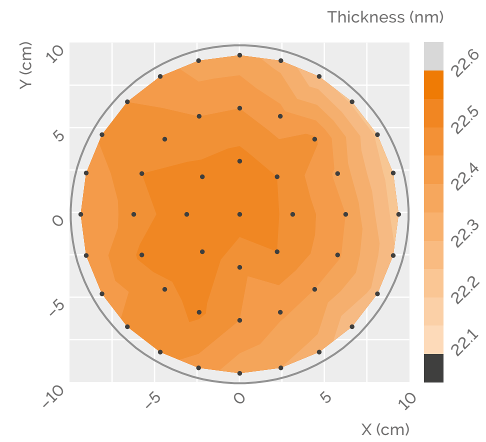


# ALD Benefits

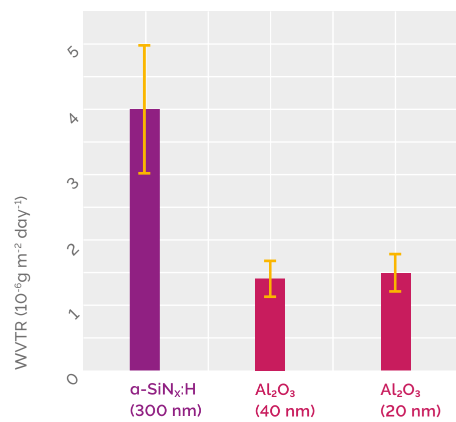
## Conformal, controlled, low pin-hole nanoscale growth

### Process benefits:

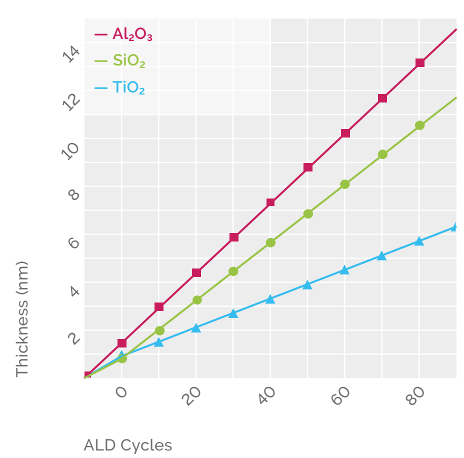
- High quality films grown with ultimate thickness accuracy, one atomic layer at a time
- Up to **200 mm wafer** with typical uniformity <±2%
- **Excellent step coverage** even inside high aspect ratio structures
- Virtually **pin-hole free** films
- **Low film impurities**; particularly with plasma ALD
- **Growth at room temperature** possible with plasma ALD
- **Low resistivity** for conductive nitride and metal films by plasma ALD
- **Superb thin film** barrier properties




High thickness uniformity for standard plasma ALD $Al_2O_3$ process on 200 mm wafers. Similar uniformities are expected for many of our plasma and thermal ALD processes.




Diffusion barriers with excellent water vapour transmission rates. 20 and 40 nm $Al_2O_3$ deposited using plasma ALD at room temperature, perform even better than a 300 nm a-$SiN_x$:H deposited by PECVD. Data courtesy of TU/e.




$Al_2O_3$, $SiO_2$ and $TiO_2$ grown at room temperature. Due to the high reactivity of plasma ALD, many materials can be deposited at lower temperature as compared to when using thermal ALD.



# ALD Process

## Process library and development

### ALD materials list

● Nitrides ● Oxides ● Metals ● Fluorides ● Sulphides

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AlN | | GaN | HfN | | | | NbN | | $Si_3N_4$ | | TaN | TiN | WN | | |
| $Al_2O_3$ | $Co_3O_4$ | $Ga_2O_3$ | $HfO_2$ | $In_2O_3$ | $Li_2CO_3$ | $MoO_3$ | $Nb_2O_5$ | NiO | $SiO_2$ | $SnO_2$ | $Ta_2O_5$ | $TiO_2$ | $WO_3$ | ZnO | $ZrO_2$ |
| | | | | Pt | Ru | | | $AlF_3$ | $MgF_2$ | | | $MoS_2$ | $WS_2$ | | |

## Precursors

### Metal precursors

Liquid or solid precursors vapours can be delivered to the reaction chamber by heating up to 200 °C.

### Non-metal precursors

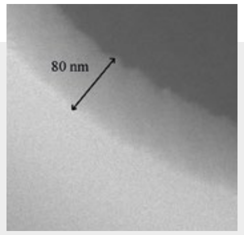
| | |
|---|---|
| $H_2O$ | Thermal Oxides |
| Ozone | Thermal Oxides |
| $O_2$ | Plasma oxides, plasma metals, thermal metals |
| $N_2$ | Plasma nitrides |
| $H_2$ | Plasma metals, plasma nitrides, some thermal metals |
| $NH_3$ | Thermal nitrides and some plasma nitrides |

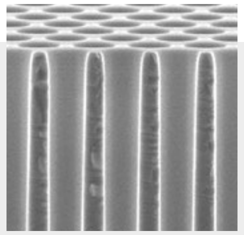
## Precursor delivery

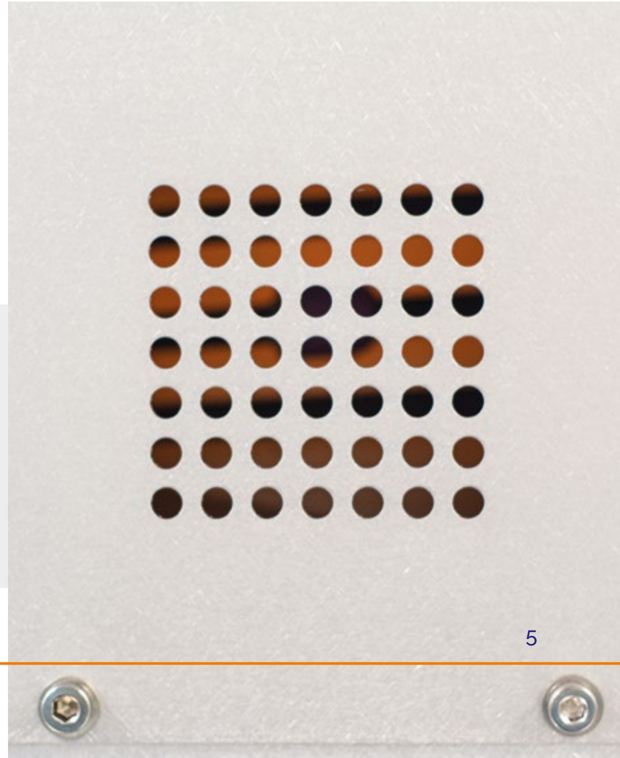
### Delivery modes:

- Multiple liquid or solid precursor delivery systems
- Vapour draw or bubbling up to 200 °C source temperature
- Precise control through fast ALD valves and wide range of plasma gas mixtures possible with independent MFC control of gases

Plasma ALD of 80 nm $Al_2O_3$ from TMA and $O_2$ plasma in a 10:1 aspect ratio deep trench capacitor structure.





# Atomic Layer Etching (ALE)

ALE is a technique designed to allow the accurate removal of one atomic layer at a time; a level of control unachievable using conventional etching.

As layers become thinner to enable the next generation semiconductor devices there is a need for ever more precise process control to create and manipulate these layers.

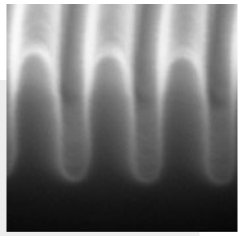
**Wide range of materials**

| Material etched | Dose gas | Etch gas |
|---|---|---|
| Si or a-Si | $Cl_2$ | Ar |
| $MoS_2$ | $Cl_2$ | Ar |
| $SiO_2$ | $CHF_3$ or $C_4F_8$ | Ar or $O_2$ |
| AlGaN/GaN | $Cl_2$, $BCl_3$ | Ar |
| AlGaN/GaN | $N_2O$ | $BCl_3$ |

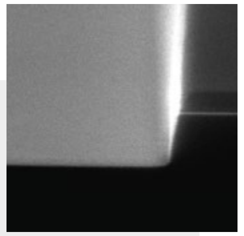
The **PlasmaPro® 100** ALE delivers this through specialised hardware including:

- Precise control of gas dose
- Excellent repeatability of low power RF delivery
- Rapid switching enabled by fast PLC

All these combine to enable etching with accuracy at the atomic scale.



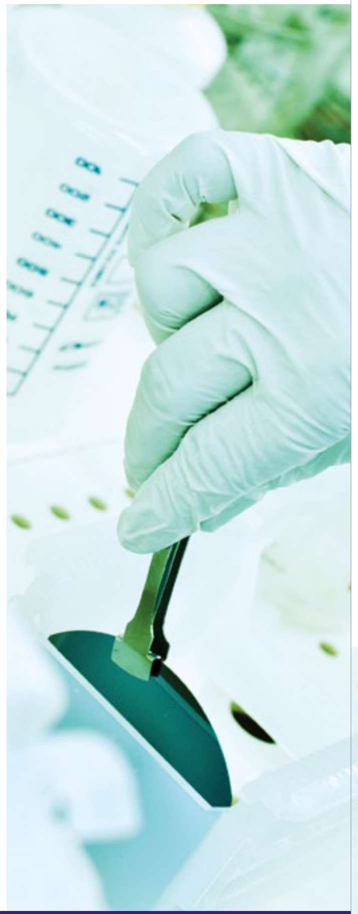
25 nm wide Si trenches etched to 110 nm depth, 150 cycles; HSQ mask still in place.



Smooth Si etch surface after 150 ALE cycles.

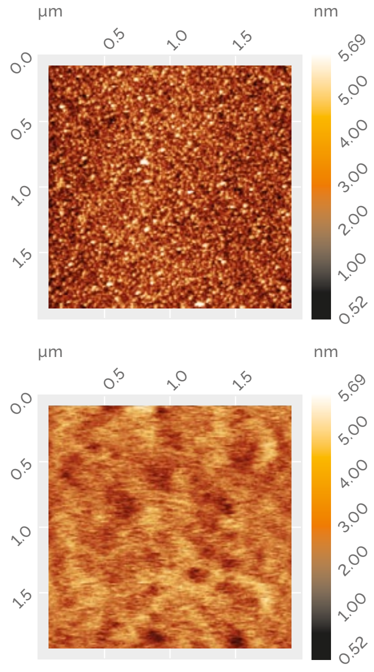
### Process benefits:

- **High accuracy** of etched depth
- Ideal for **nanoscale layer removal**
- Possibility of **single atomic layer etch** (e.g. for 2D materials)
- **Smooth etch** surfaces
- **High selectivity**
- **Low damage**
- **Excellent uniformity**
- **Minimal aspect ratio** dependence

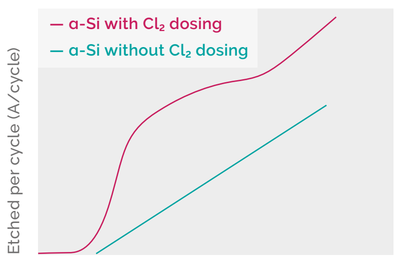


# ALE Process

## Process library and development




AFM images show AlGaN surface roughness reduced by 0.3 nm within 30 cycles.




Graph showing true ALE plateau when etching a-Si, the precise control of the RF power is essential to achieve repeatable ALE.

## ALE cycle

1 **Dose**

Chamber is given a short dose with a chemically reactive species ($Cl_2$ for GaN, AlGaN or Si). This forms a layer on the substrate surface

2 **Purge**

Excess $Cl_2$ is pumped away to leave just a layer on the substrate surface

3 **Etch**

A small amount of DC bias power is applied causing Ar ion bombardment to remove the top layer and leave a fresh substrate surface.

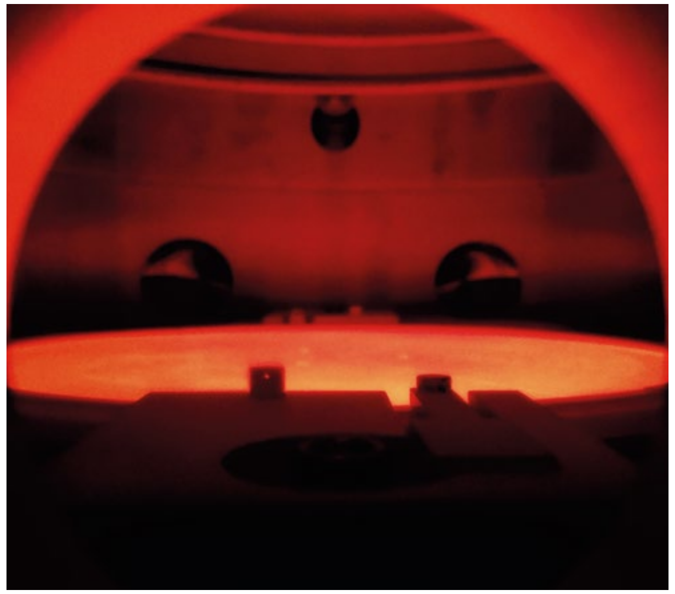
4 **Pump** byproducts

Pump out step to remove all by-products from the chamber before a fresh dose of $Cl_2$ is introduced.

# Chemical Vapour Deposition (CVD)

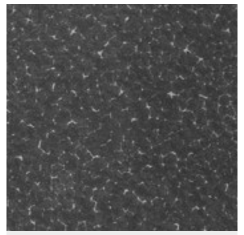
## CVD systems for growth of nanomaterials

**PlasmaPro® 100** Nano is a high temperature CVD/PECVD system tailored for high quality deposition of nanostructured materials and Silicon based thin films.

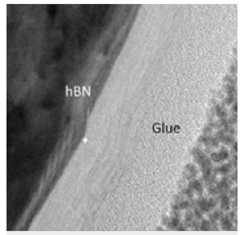


### Features:

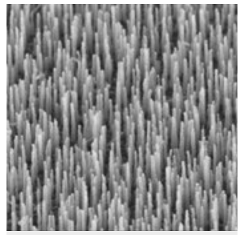
- Cold wall design with showerhead based uniform gas delivery
- Plasma options for PECVD and chamber cleans: Parallel Plate (capacitively coupled) or remote plasma (ICP)
- Vacuum load lock for quick sample exchange
- Excellent temperature uniformity
- Optional multiple liquid/solid source delivery systems for growth of $MoS_2$, $MoSe_2$ and other TMDCs
- Variable sample sizes up to maximum 200 mm wafers
- Multiple view ports for diagnostics



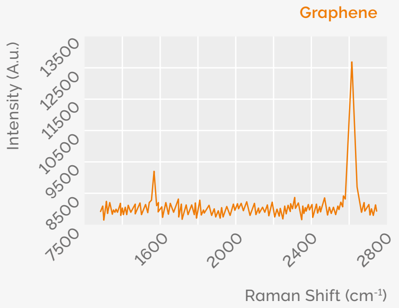
CVD of graphene domains growing on copper substrates.

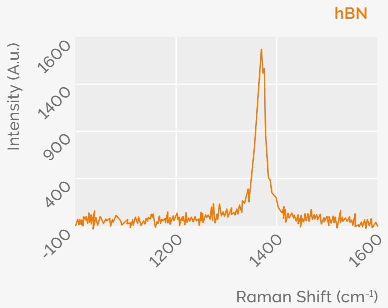


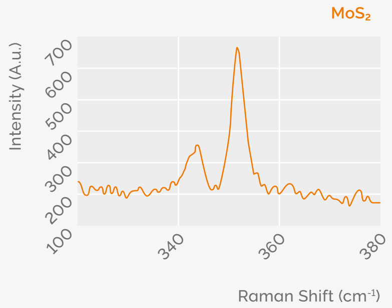

CVD Growth of hBN.



CVD ZnO nanowire growth using DEZn precursors.



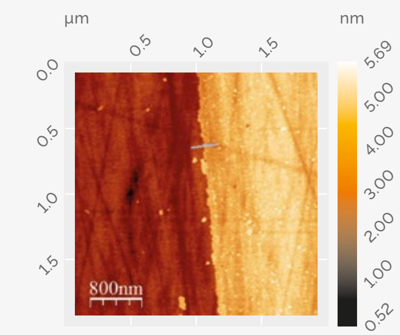



# Chemical Vapour Deposition (CVD)

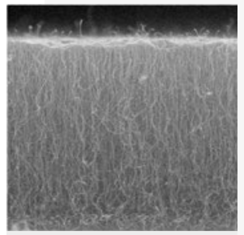
## CVD systems for growth of nanomaterials

### Wide range of materials

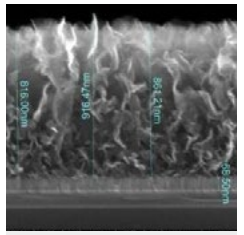
| | 700°C table | 800°C table | 1200°C table |
|---|---|---|---|
| Thin film process | $SiO_x$, $SiN_x$, a-SiC, a-Si, µc-Si, polySi* | $SiO_x$, $SiN_x$, a-SiC, a-Si, µc-Si, polySi | $SiO_x$, $SiN_x$, a-SiC, a-Si, µc-Si, polySi |
| 1D Nanomaterials | MWNTs, Si, Ge NWs, ZnO NWs | MWNTs, SWNTs*, Si, Ge NWs | MWNTs, SWNTs, Si, Ge NWs |
| 2D Nanomaterials | NA | Nano-crystalline Graphene, Vertical Graphene | Graphene, hBN, $MoS_2$, $WS_2$, Vertical Graphene, Nano-crystalline Graphene |




CVD growth of 2D $MoS_2$.

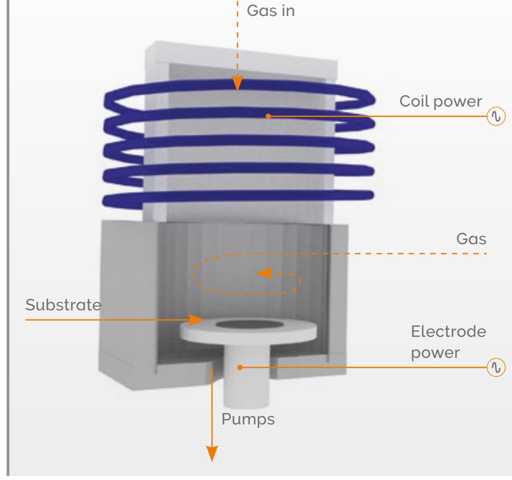


Dense Carbon Nanotubes grown by PECVD.

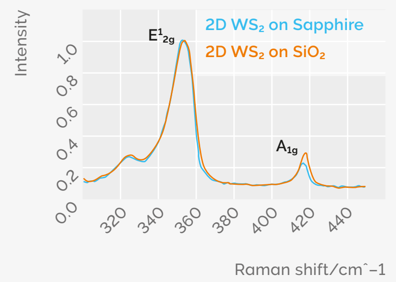


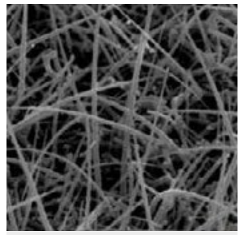
PECVD of vertically aligned graphene.

**PlasmaPro® 100** Nano chamber with inductively coupled (remote) plasma enhancement.



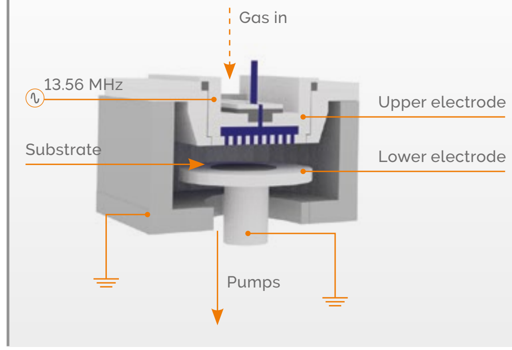

Raman shift of CVD of $WS_2$.



CVD growth of Silicon nanowires using Au nanoparticle catalysts.

**PlasmaPro® 100** Nano chamber with capacitively coupled plasma hardware for PECVD processing.



# Hardware

## Plasma processing systems that provide a complete solution to ASP

### FlexAL System

- Remote plasma & thermal ALD in one flexible tool
- Automated 200 mm load lock
- Clusterable for vacuum transfer of substrates
- Optional cassette to cassette handling

### PlasmaPro® 100 ALE

- Superb etch depth control
- Smooth etch surface
- Low damage process
- Digital/Cyclical etch process
- High selectivity
- Process capability up to 200 mm wafers
- High aspect ratio (HAR) etch process

Inside view of precursor pot for liquid/ solid precursors.

### PlasmaPro® 100 Nano

- Excellent uniformity
- Options of a 700 °C, 800 °C, or 1200 °C table
- Sample sizes up to 200 mm
- Vacuum load lock—quick sample exchange
- Optional liquid/solid source delivery system for growth of $MoS_2$ $MoSe_2$ and other TMDCs



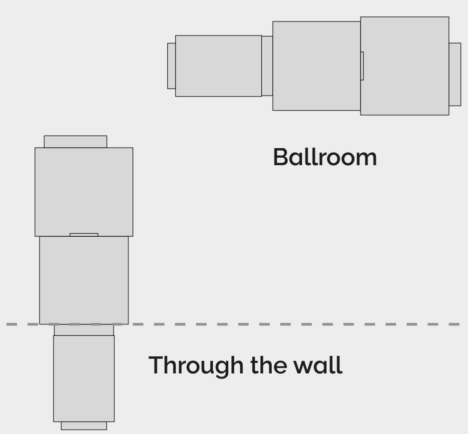
# Configuration Options

## Systems easily configured for cutting edge production or research

We provide unique cluster capability or stand-alone systems enabling the manipulation of matter with atomic scale precision on a production scale.

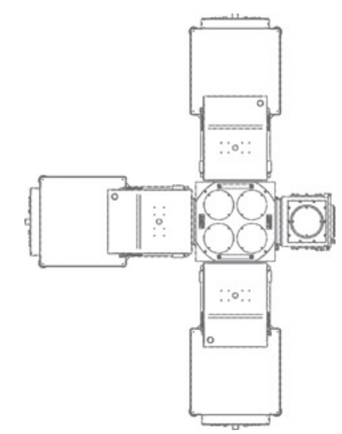
1. ALD thermal & plasma
2. ICP CVD & thermal CVD
3. ALE
4. Hex handler


Configurations can be located entirely within the cleanroom or through-the-wall

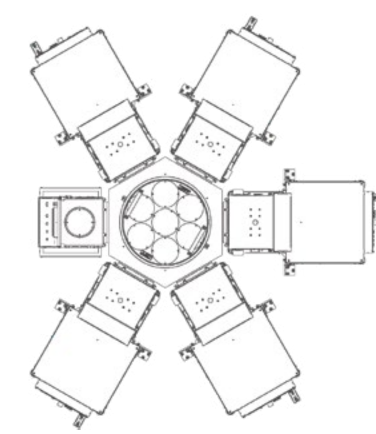



### Cluster options

4-way square handler



6-way hex handler



# Worldwide Service

Oxford Instruments is committed to supporting our customers' success. We recognise that this requires world class products complemented by world class support. Our global service force is backed by regional offices, offering rapid support wherever you are in the world.

**We can provide:**

- Flexible service agreements to meet your needs
- Tailored system training courses
- System upgrades and refurbishments
- Immediate access to genuine spare parts and accessories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