In situ control of deposition rate and chemical composition of compound materials and alloys during PVD

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Overview

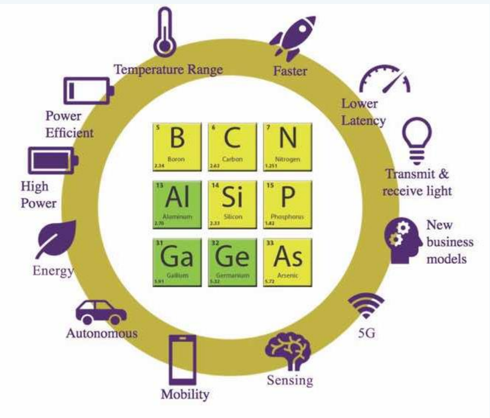
US Pat 10,408,744 EU Pat 3,417,478B1

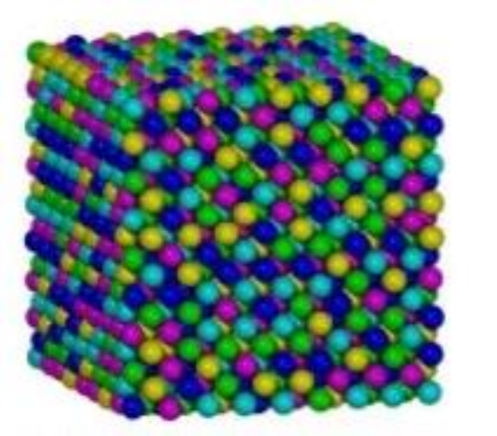
- AccuStrata’s AtOMS: a novel in situ process control tool for compounds and alloys
- Pain Points in Advanced Materials and Multilayer Coatings
- Combined Atomic Absorption + Plasma Optical Emission as a novel solution
- AtOMS: Novel *in situ* Atomic Absorption Process Control Technology
- AtOMS integrated into a PVD process
- Differentiation from the legacy *in situ* techniques: QCM, OMS, PES, XRF
- Summary

See us at Booth 310

New generation advanced materials

- ✓ Compound wide-band semiconductors. i.e. GaAs, AlInGaP, AlInGaN, $LaAlO_3$, CdTe, CIGS, YBCO, $LiCoO_2$, etc.
- ✓ High entropy superalloys (HESA) and atomic mixtures of 5-6 elements
- ✓ Extremely thin films (<10A) and engineered interface layers
- ✓ Very thick films and coatings > 50 micron
- ✓ Structured/patterned films
- ✓ Films of ceramic composites, nanocomposites and rough surfaces
- ✓ Films and coatings on non-symmetric or complex-shape parts or substrate motions





Major process control pain points

- ❑ Control concentration and energetics of individual elements and radicals in the PVD plum
- ❑ Control chemical composition and its uniformity as deposition transpires
- ❑ Be agnostic to type of substrate and its motion w/o shadowing substrate
- ❑ Achieve run-to-run repeatability of the material characteristics
- ❑ Deploy cutting edge active learning and reasoning algorithms

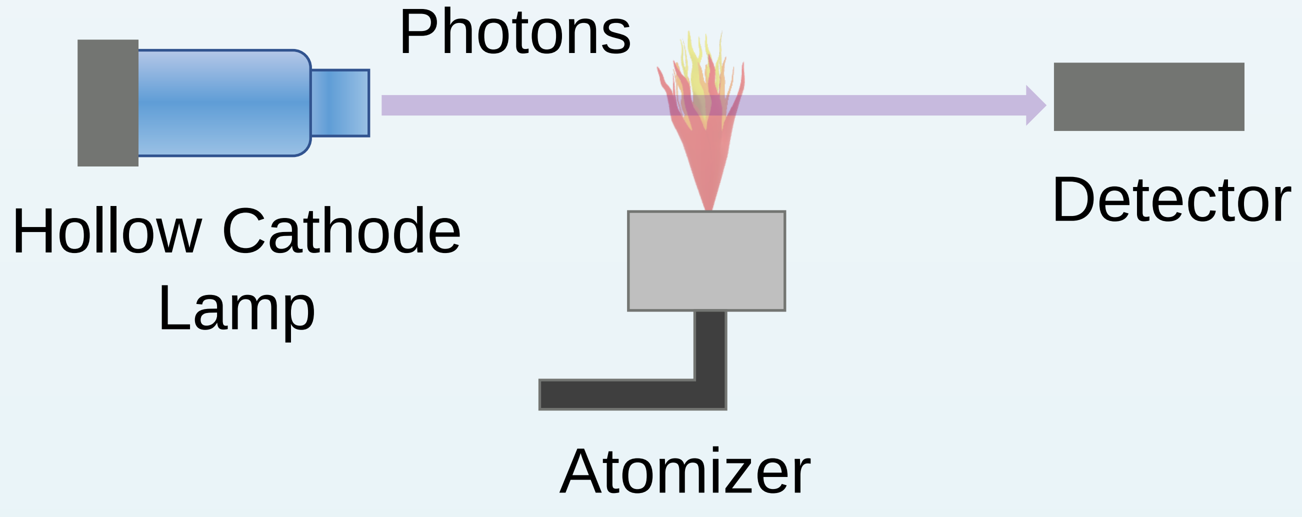
The Most Critical Parameters for Compound Materials and Alloys

- Deposition Rates and Their Uniformity and the Energetics of the Individual Elements
- Resultant Film Chemical Composition and Morphology, Their Homogeneity and Uniformity

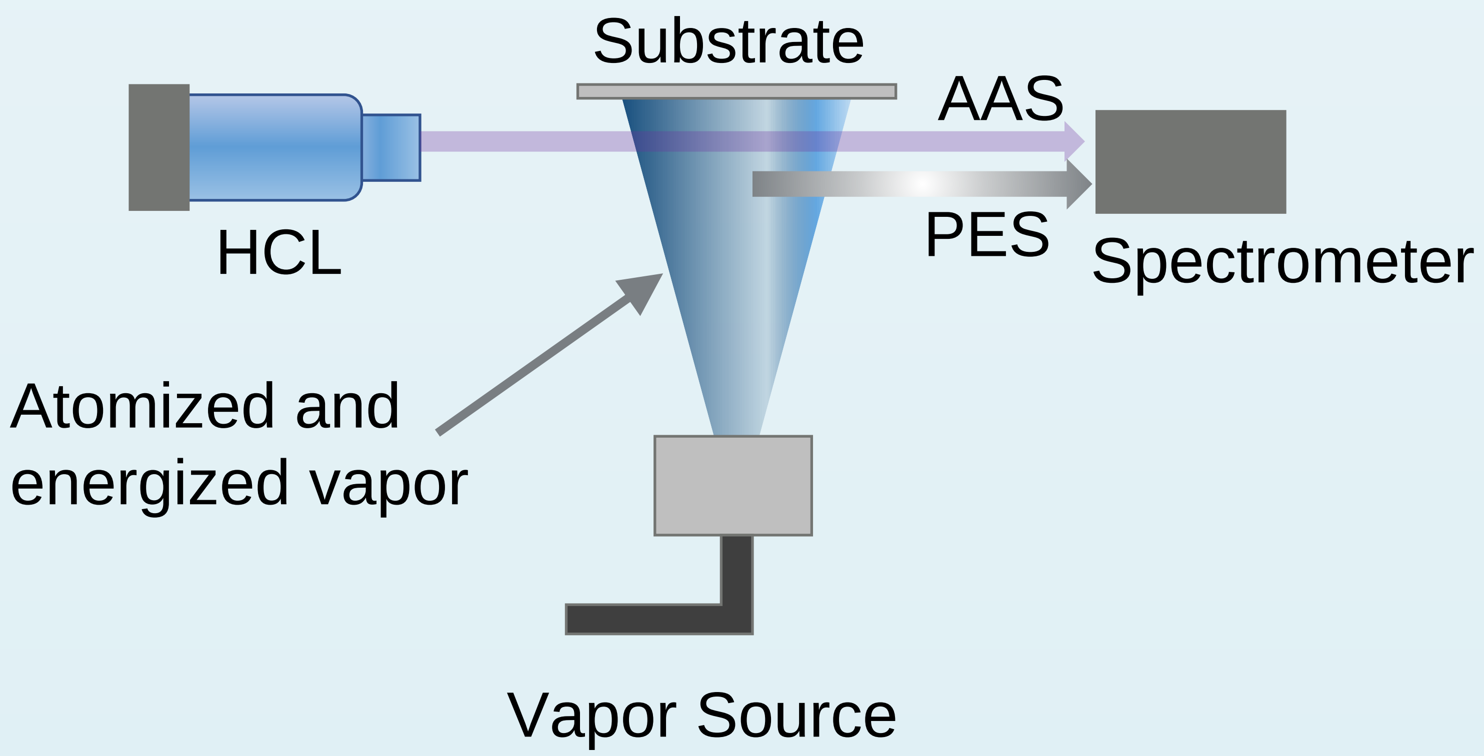
Atomic Spectroscopy as in situ technique offers a solution

- AAS: Traditional analytical tool for identifying small trace of elements
- Uses atomization to break down components into individual atoms
- Element specific light (Hollow Cathode Lamp - HCL) traverses the atomized material.
- HCL for over 60 metal and metalloid elements are available, plus over 30 combinations of 2 and 3 elements
- The element's AA is related to atomic concentration (Beer-Lambert Law), atomic flux and deposition rate with no or little tooling factors
- PVD processes are atomized and energetic processes
- PVD emits light (POE) specific to elements and radicals in the plum
- PVD provides excellent opportunity for atomic spectroscopy as a process control tool
- AA can be measured simultaneously with plasma emission (PES) to detect radicals and energetics of particles

Traditional Approach



Physical Vapor Deposition



AAS + PES compared to AAS or PES alone

AAS alone

Advantages:

- 10-20 times stronger than PES for most metals and metalloids
- High accuracy for the AA of the element of interest
- Works well with all PVD processes (dep. and etch)

Disadvantages:

- Additional hardware and calculation complexity
- Added cost compared to PES alone

PES alone

Advantages:

- Works well with most PVD etching (not deposition) processes
- Simple and easy to install hardware w/o equipment refurbish
- Low cost

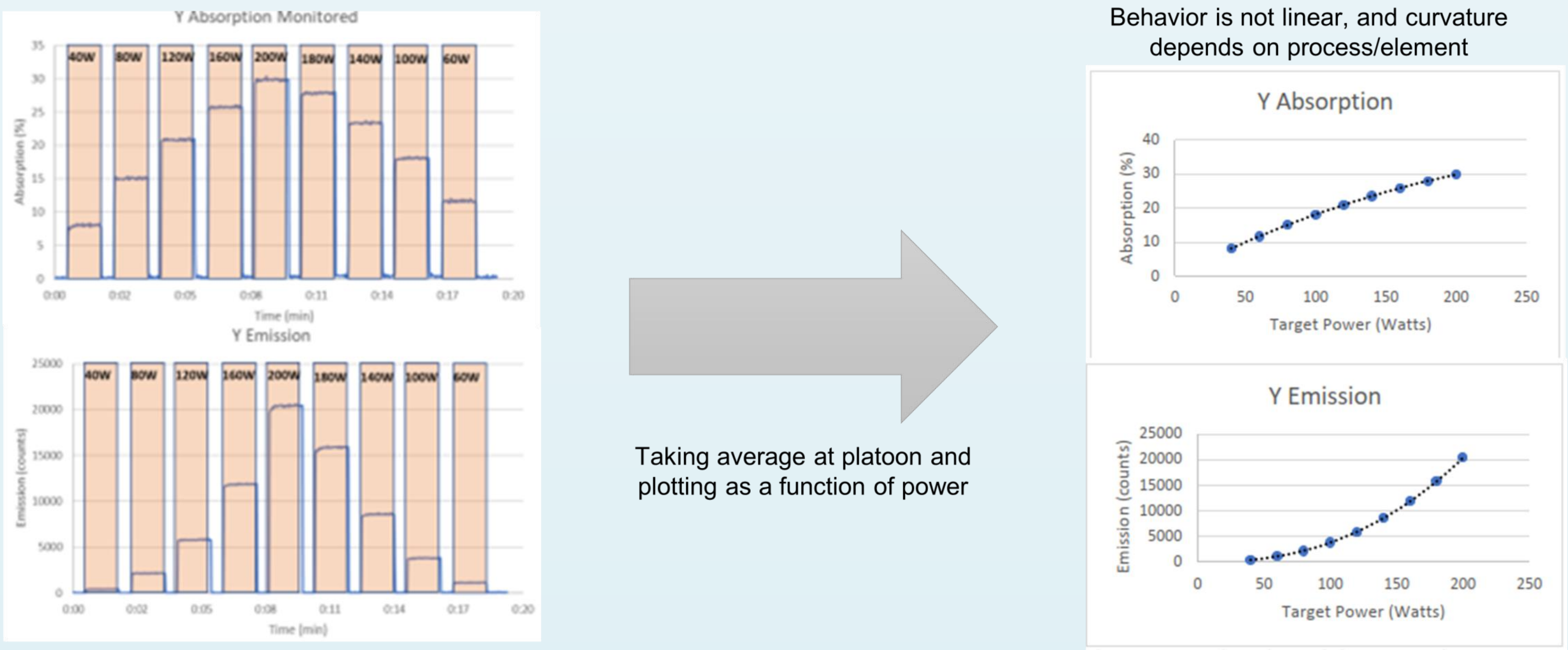
Disadvantages:

- Strongly varies with process conditions: T^{o}, pressure, gases
- Only 0% calibration possible, no quantitative measurements for deposition

Combined AAS and PES – AccuStrata's solution

Advantages:

- Works well with both PVD deposition and etching
- Allows 100% and 0% reference for quantitative deposition rate
- Dep. rate of up to 6 individual elements calculated with no/less tooling factors
- Characterize the energetics of the particles of interest
- Calculate chemical composition in real time
- Accounts for potential viewport contamination
- Ideal for deep learning and advanced software implementation



Magnetron sputtering of YSZ

AAS+POE - perfect application to PVD of thin films and coatings, especially WBS and HESA

AtOMS: AccuStrata's In Situ Control of PVD Processes

Processes in Vacuum

Physical Vapor Deposition

- Magnetron Sputtering
- Ion beam Sputtering
- Electron Beam Evaporation
- Thermal Evaporation
- Laser Pulse Deposition
- Molecular Beam Epitaxy
- Implantation

Etching/Ablation Processes

- Ion Etching
- Laser Ablation

Coating Types

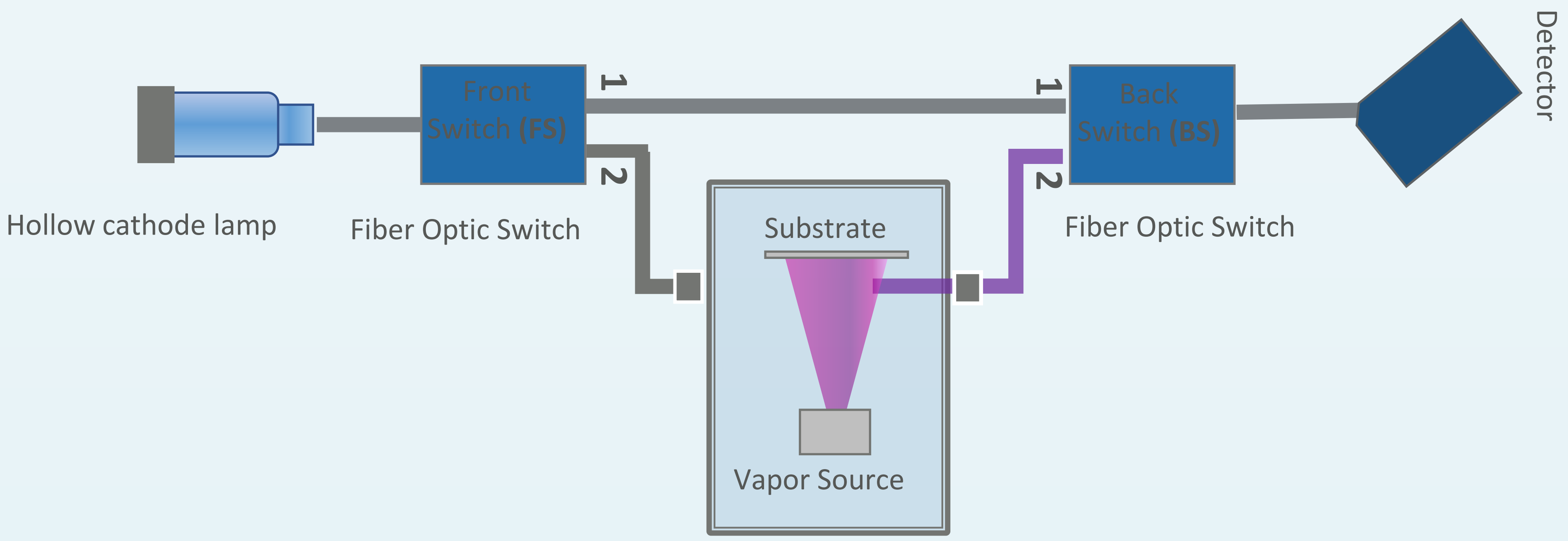
- Complex Multilayers
- Compound Materials / Alloys
- Opaque or Semi-Transparent TF
- Extremely Thin Films / Multilayers
- Engineered Interface Layers
- Patterned TF and Coatings
- Gradient Profile Coatings
- Extremely Thick Coatings (>100 μm)

Substrates

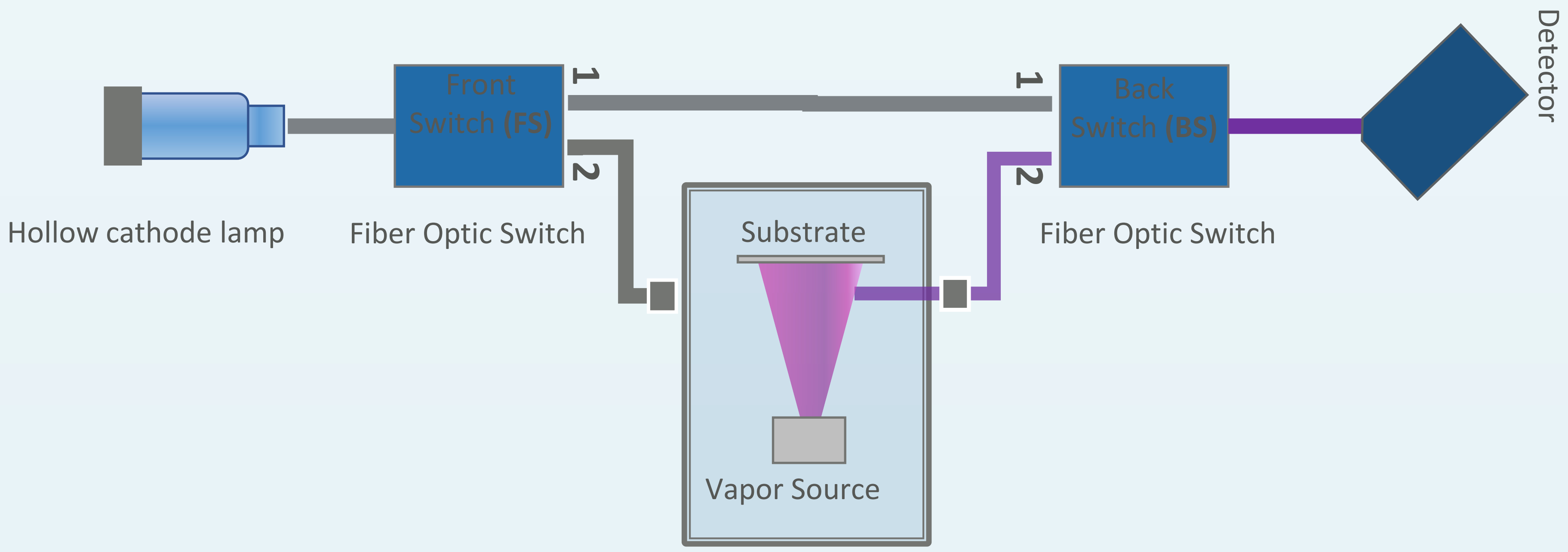
- Agnostic to Type, Shape or Motion
- CMC, Nanocomposites, Graphene

AtOMS: 4-stage data acquisition duty cycle

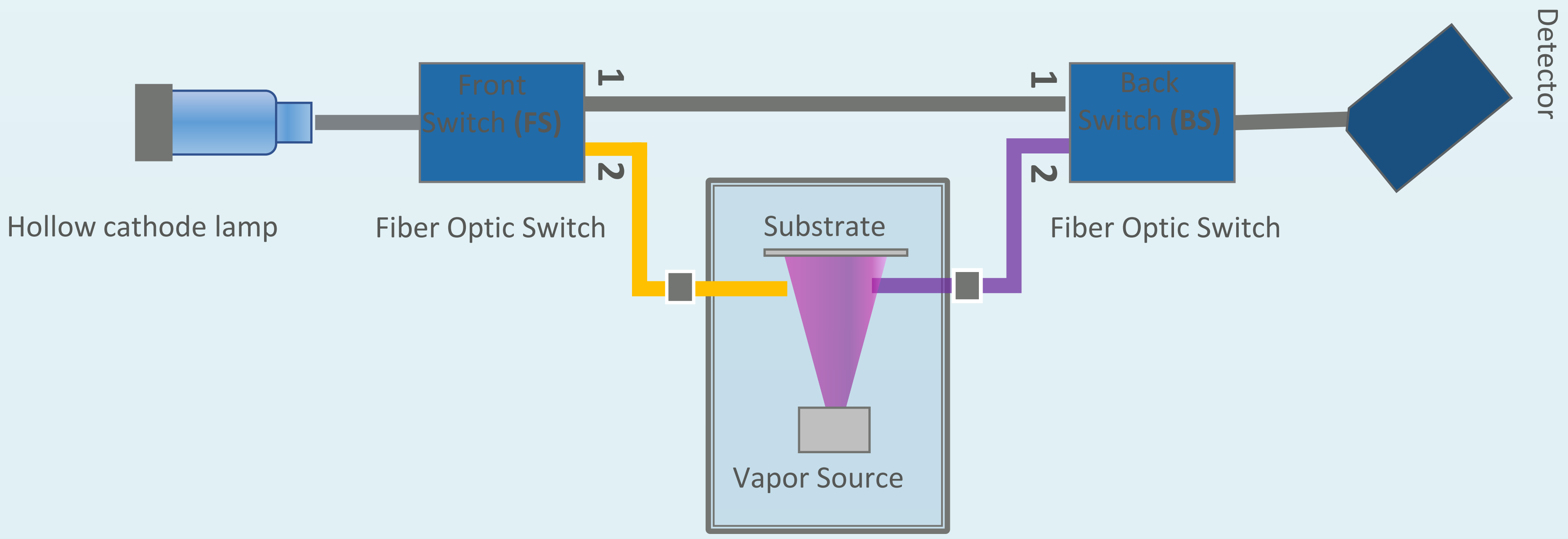
1. HCL 100% Reference: Configuration FS1 BS1



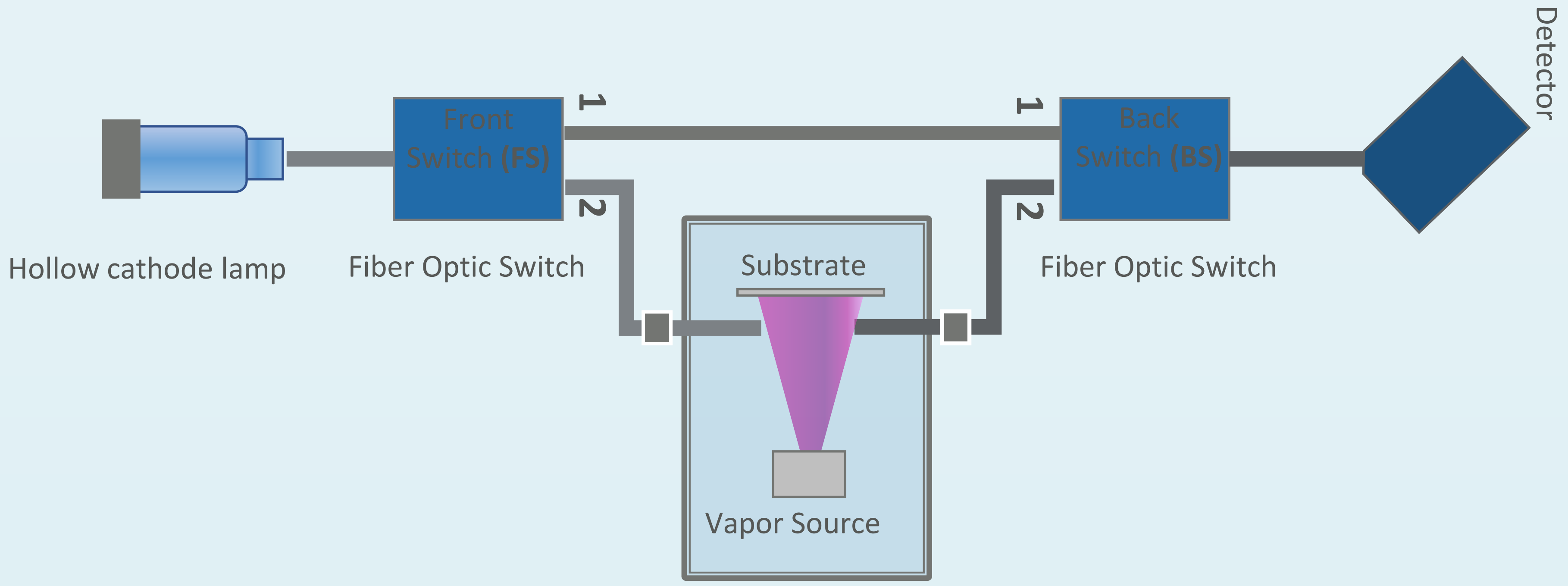
3. PES: Configuration FS1 BS2



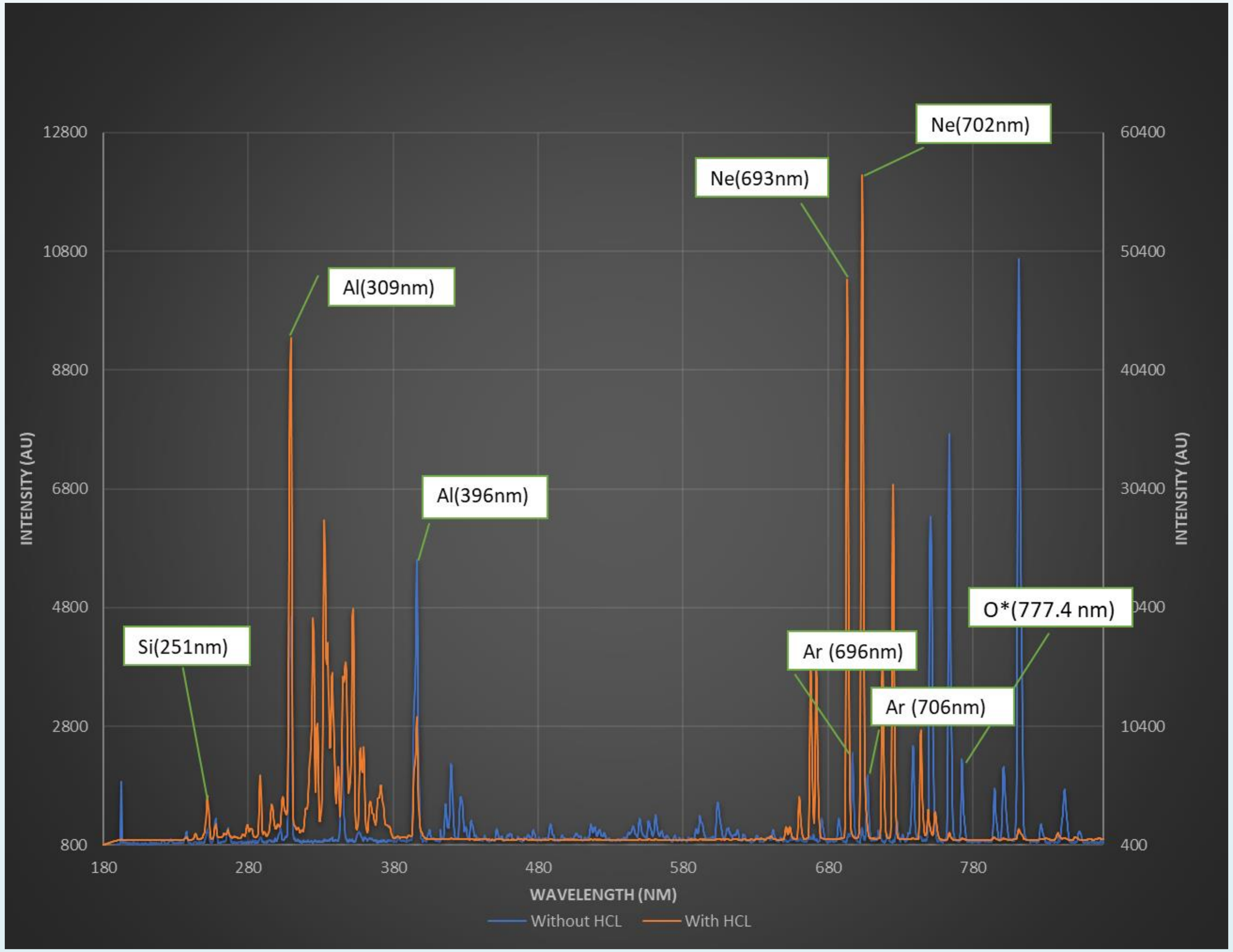
2. Dark Reference: Configuration FS2 BS1

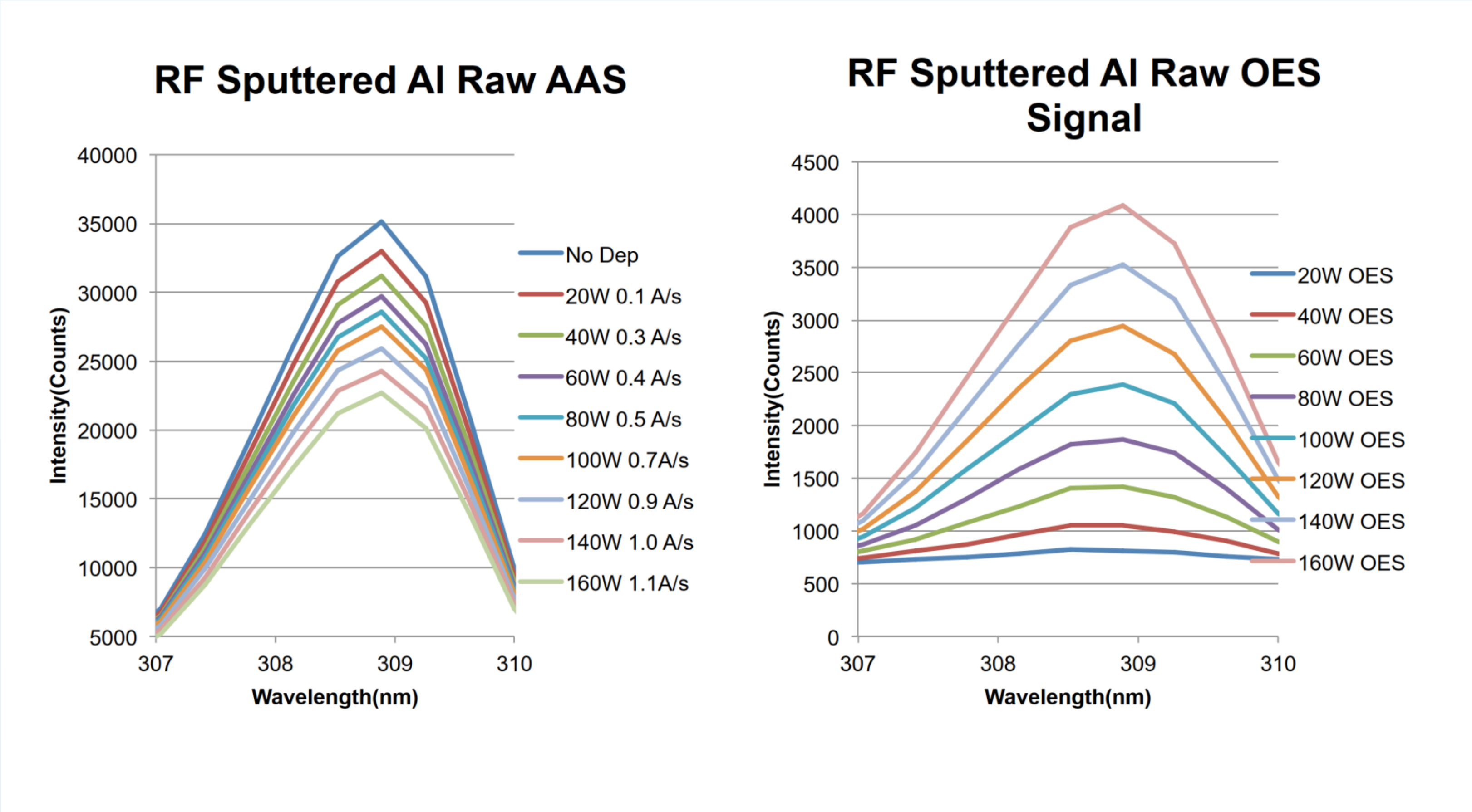


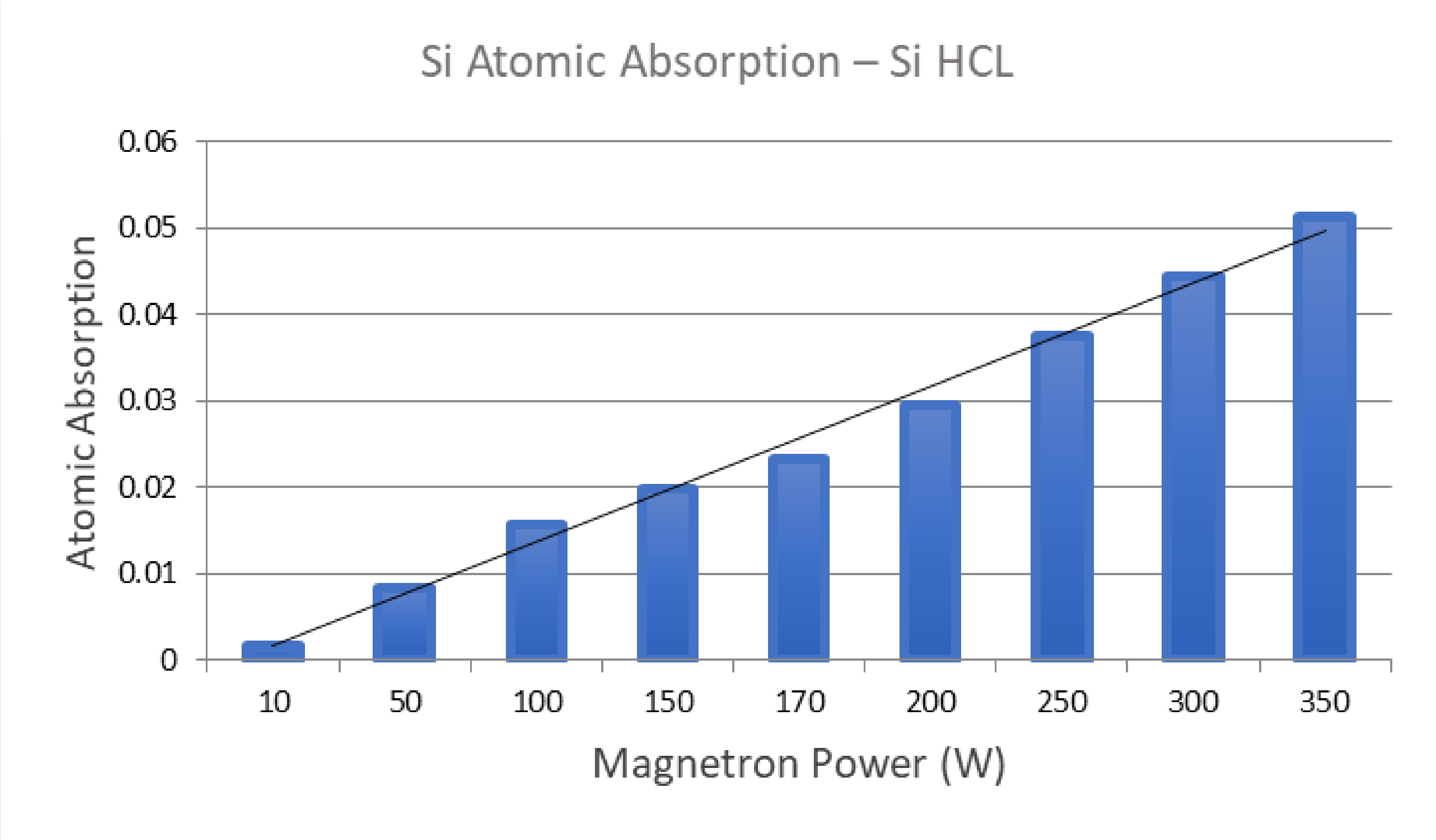
4. AAS + PES: Configuration FS2 BS2



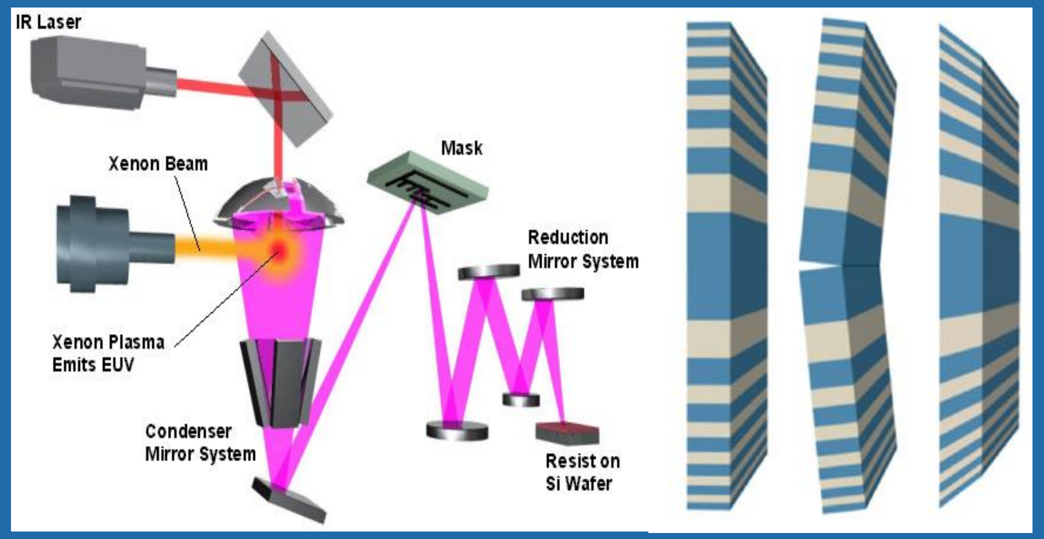
Acquired spectra during monitoring Al/Si compound



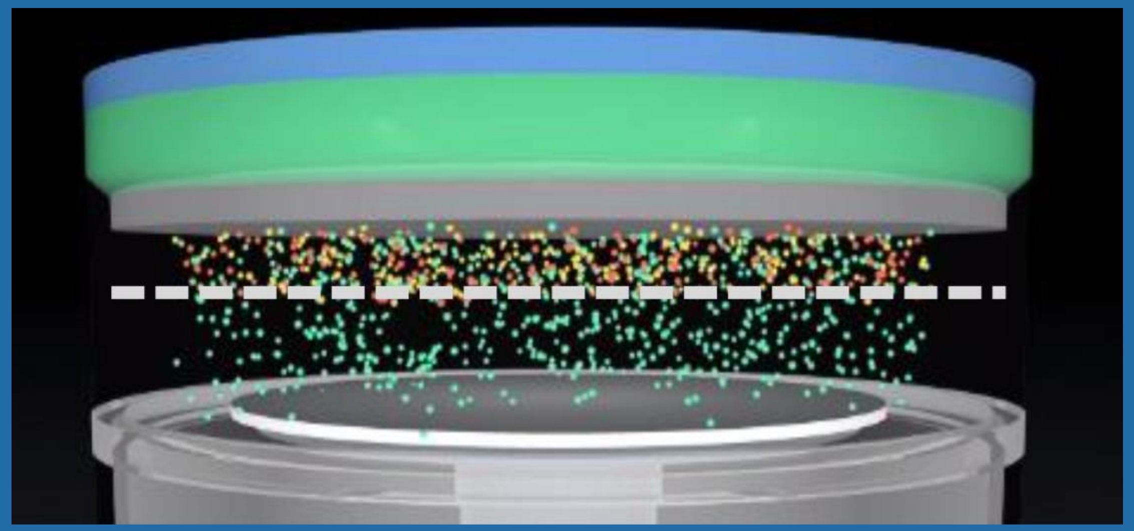




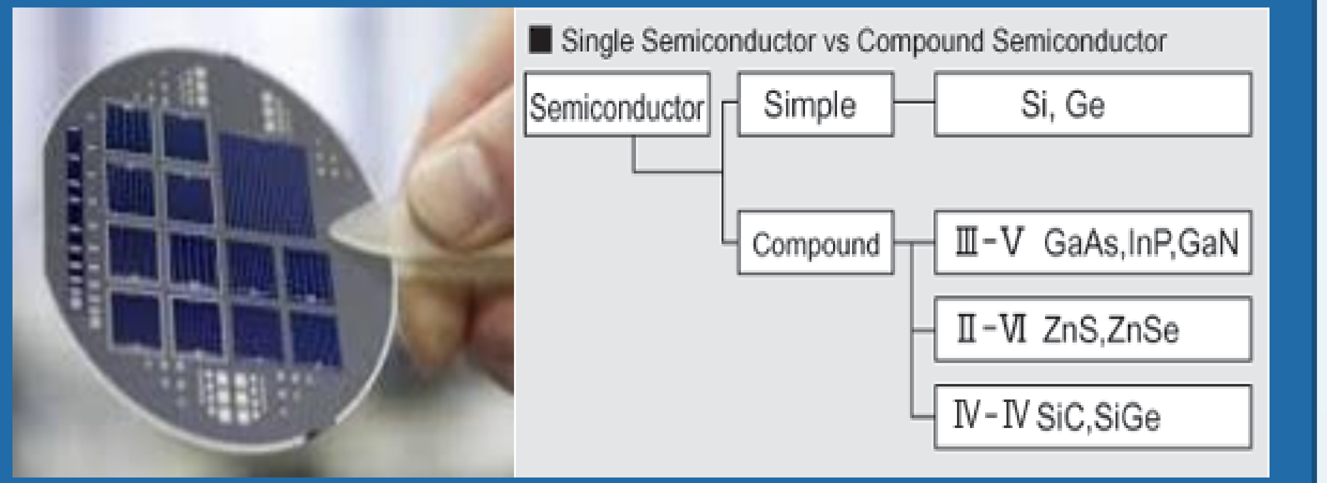
Processes that benefit from AAS+PES



Optics for X-Ray and EUV lithography

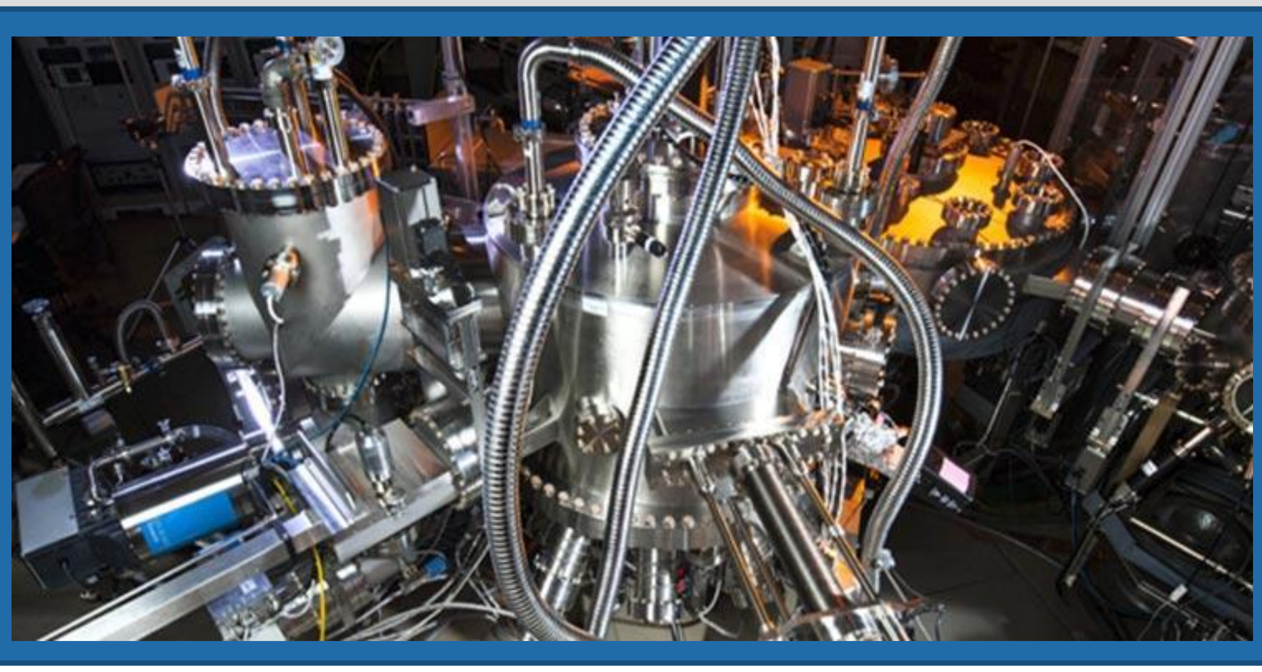


Next-gen semiconductor deposition, etching and cleaning processes

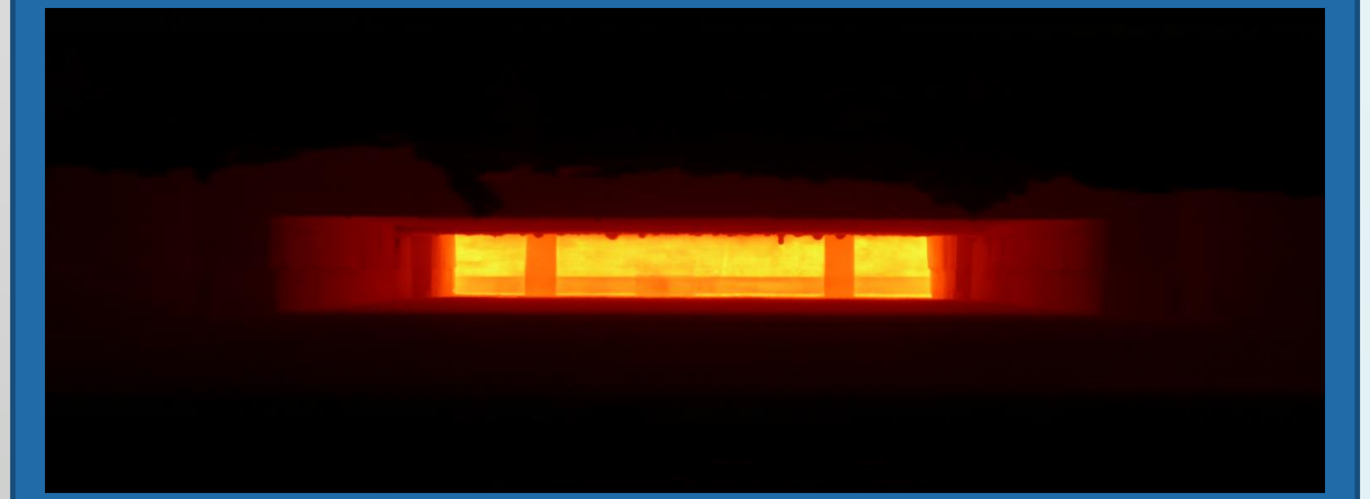


Compound materials and wide-band semiconductors

Deposition of super-alloys and HE alloys

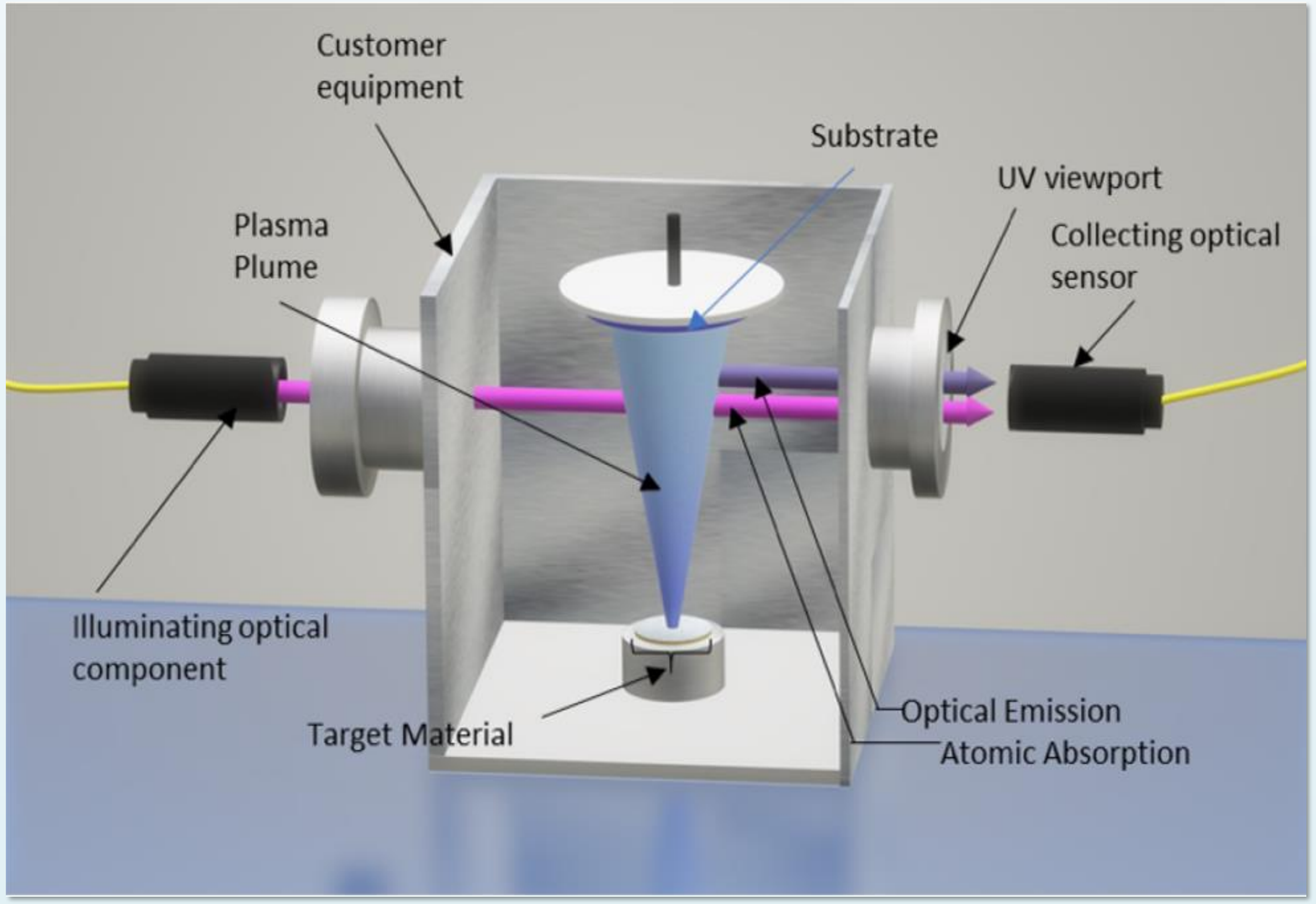


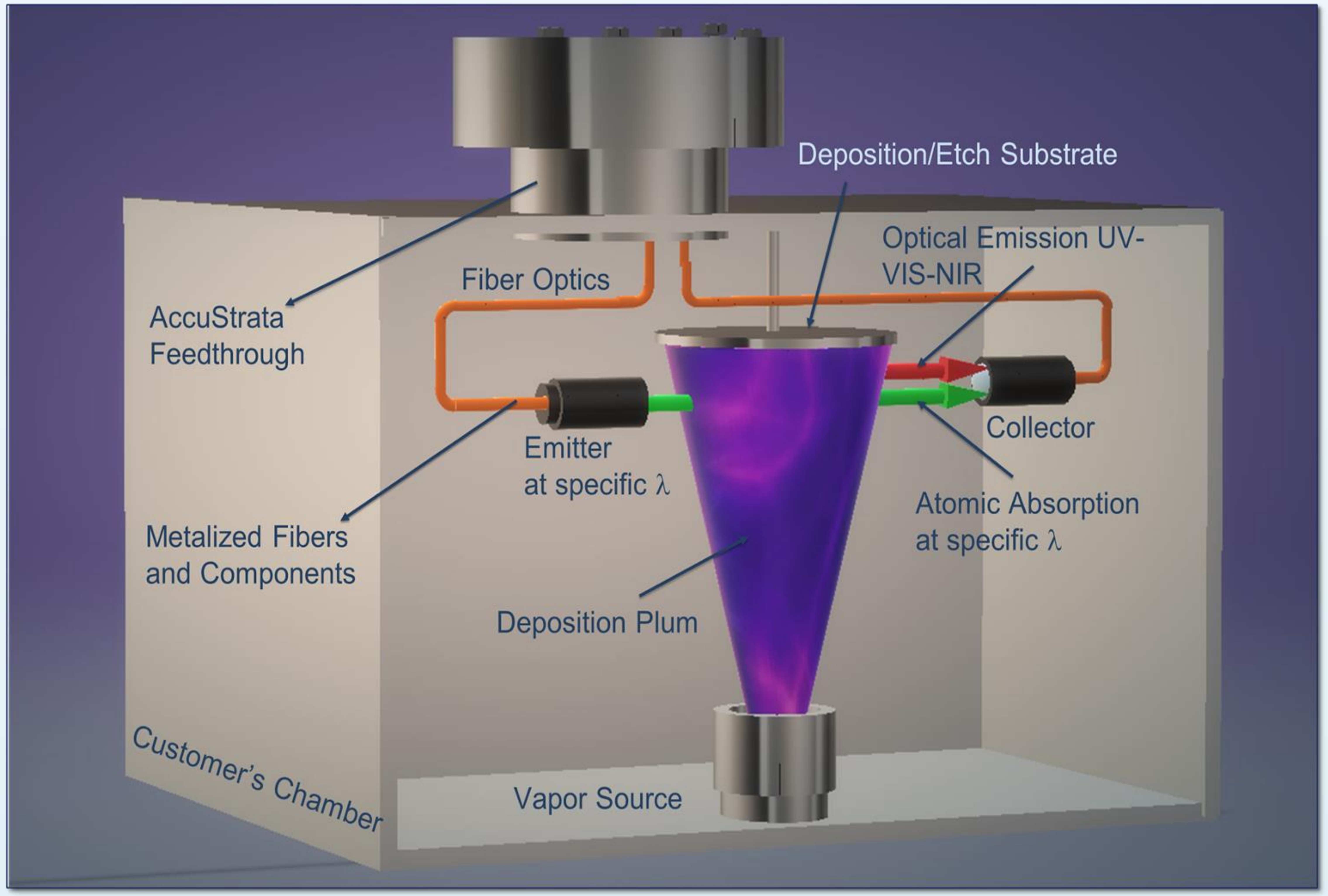
R&D process development and process tuning



Process monitoring and control with predictive analytics

Installation approaches: external and internal



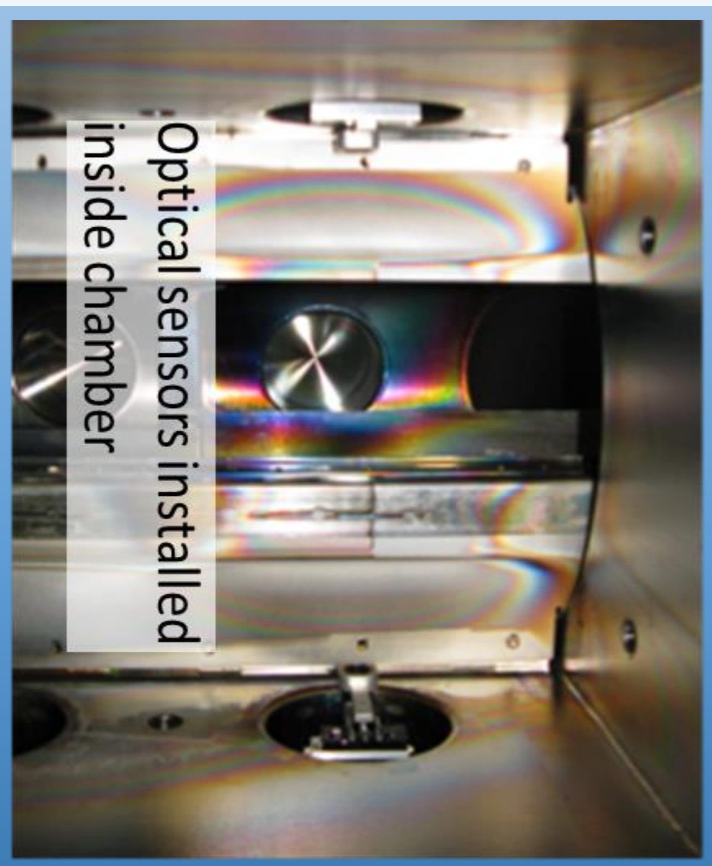


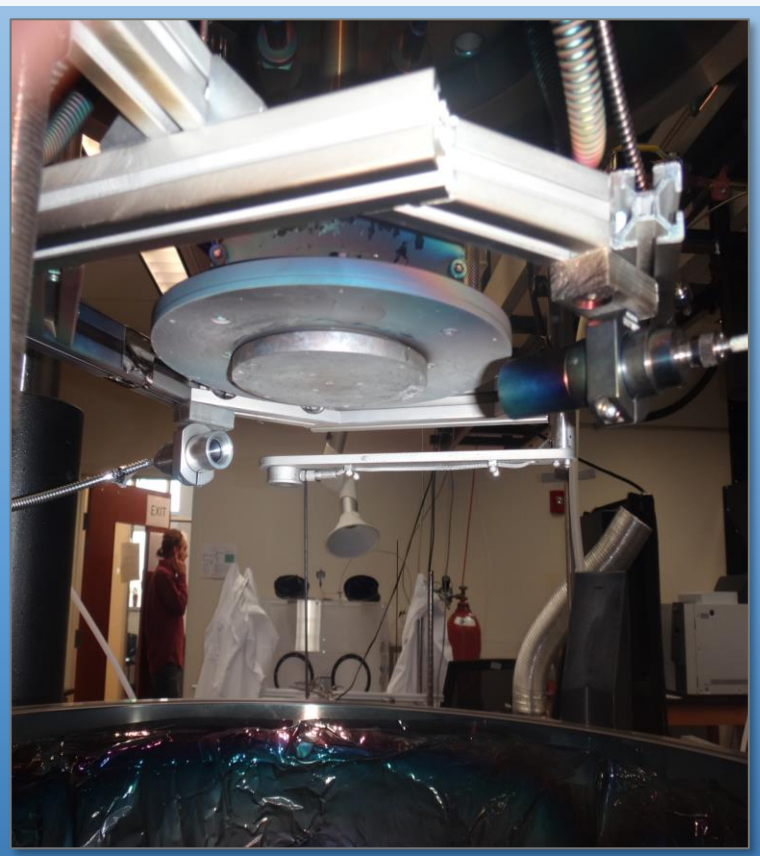
External installation with QZ viewports

Internal installation with metal-coated fibers

Examples of current installations

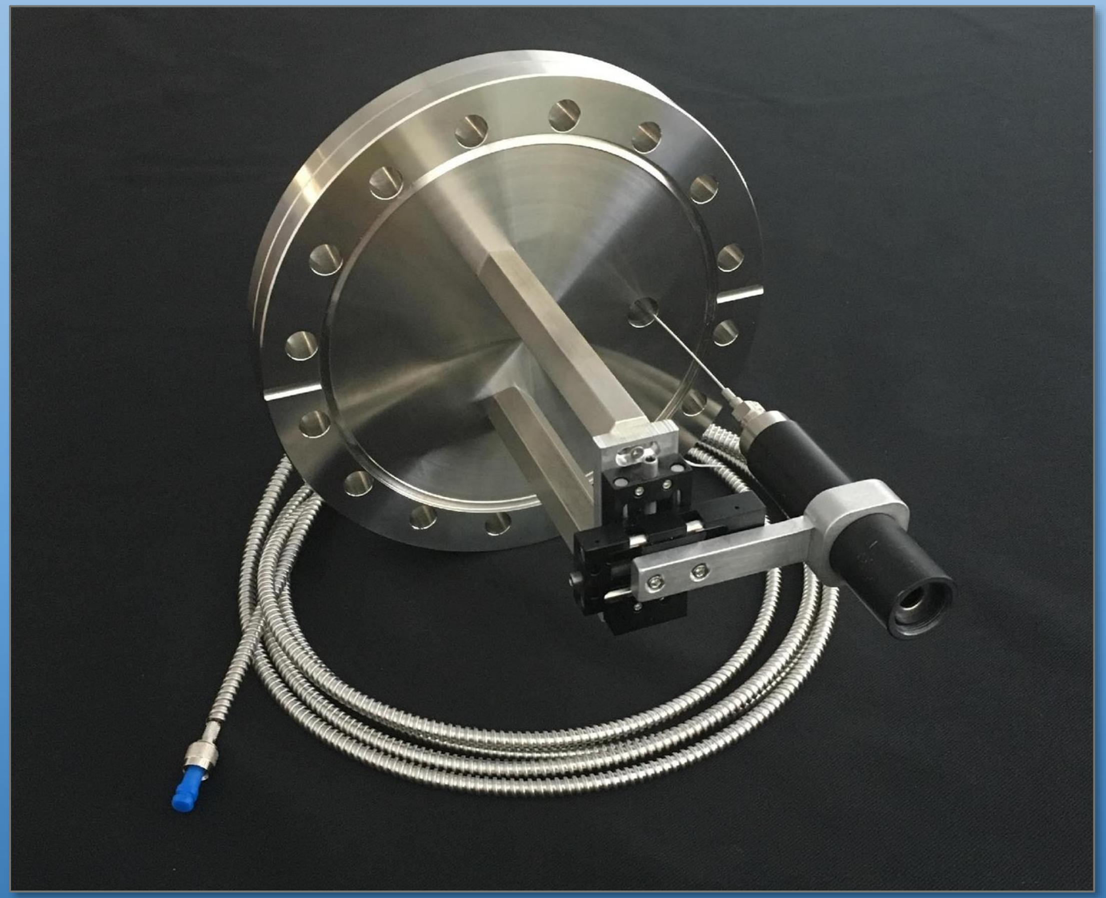

Installations Outside Chamber



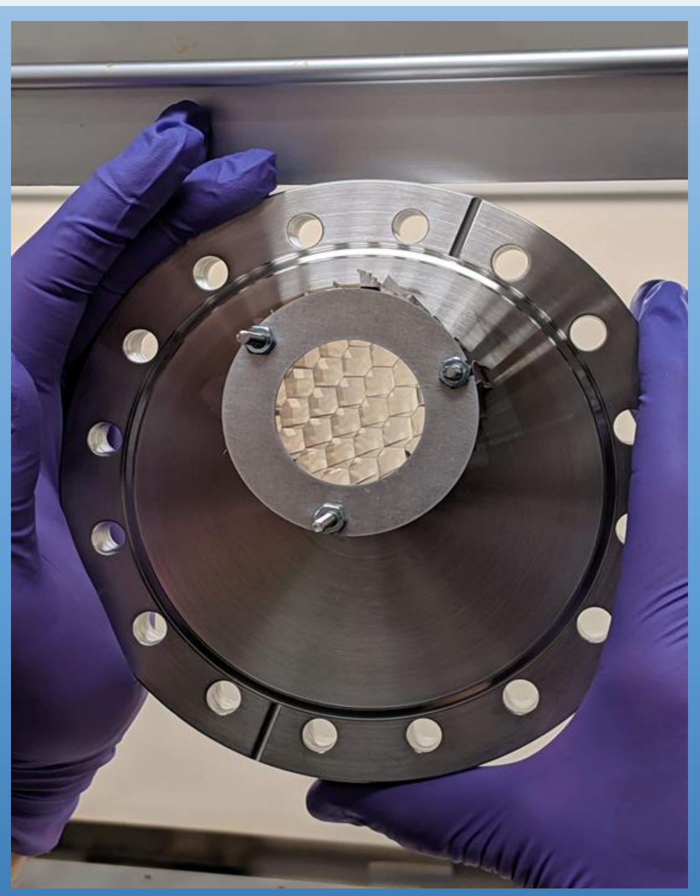


Installations Inside Chamber

Periscopic Installation Outside Chamber



Sensor with Protective Apertures for Inside Chamber




Honeycomb Protection of Viewports

AtOMS compared to substrate OMS and QCM

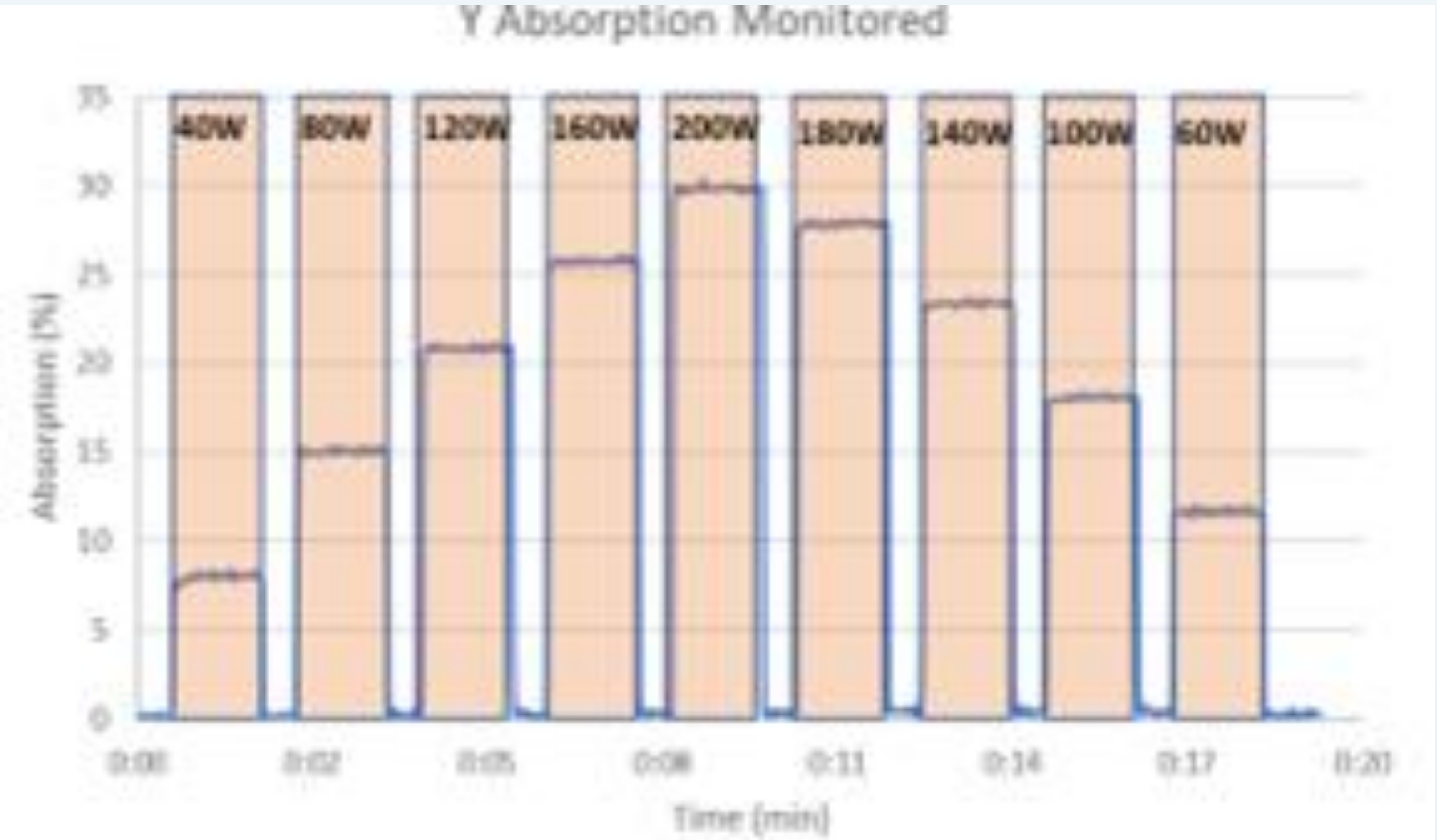
Comparisons

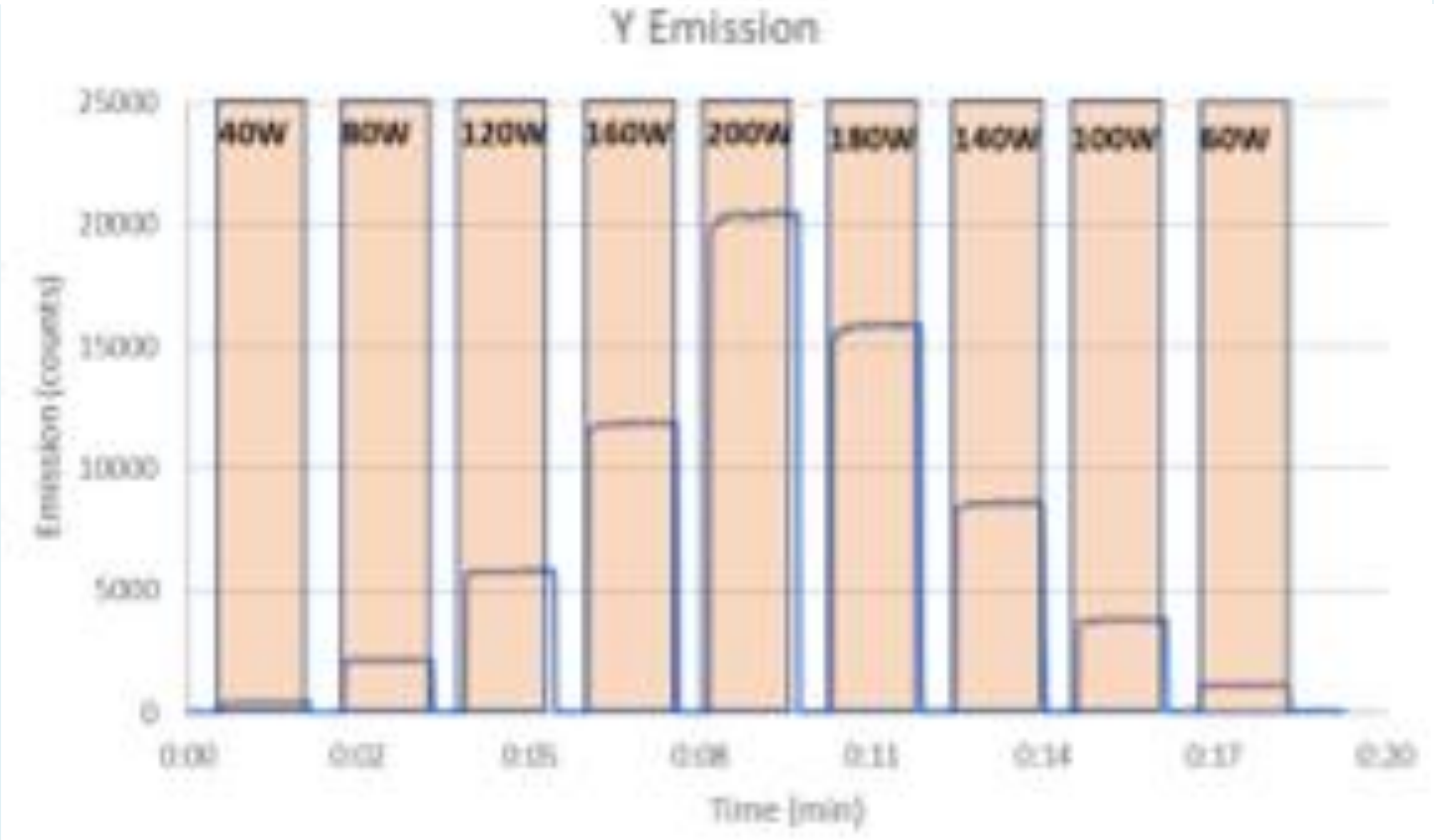
SOME COMPETITIVE TECHNOLOGIES:

- Quartz Crystal Monitoring QCM
- *In Situ* Reflectometry of Substrate
- *In Situ* Ellipsometry
- Plasma Emission Spectroscopy
- X-Ray Fluorescence (XRF)
- Reflective High Energy Electron Diffraction (RHEED)

Capabilities	AtOMS	Direct Monitoring of Substrates	Quartz Crystal Monitoring
Simultaneous Multi-Element Deposition Rate Monitoring	✓	✓	✗
Elemental Concentration in Multi-Element Co-Deposition	✓	✗	✗
In Situ Monitoring of Film Chemical Composition	✓	✗	✗
>60 Different Chemical Elements can be Uniquely Monitored	✓	✓	✓
Monitoring Extremely Thin Film (<20A)	✓	✗	✗
Monitoring Very High Deposition Rates	✓	✗	✓
Deposition Rate Accuracy of ± 0.005 A/Sec	✓	✗	✓
Composition Accuracy ± 0.025 Atomic %	✓	✗	✗
Monitoring Optically Opaque Materials, Metals, and High Entropy Alloys	✓	✗	✓

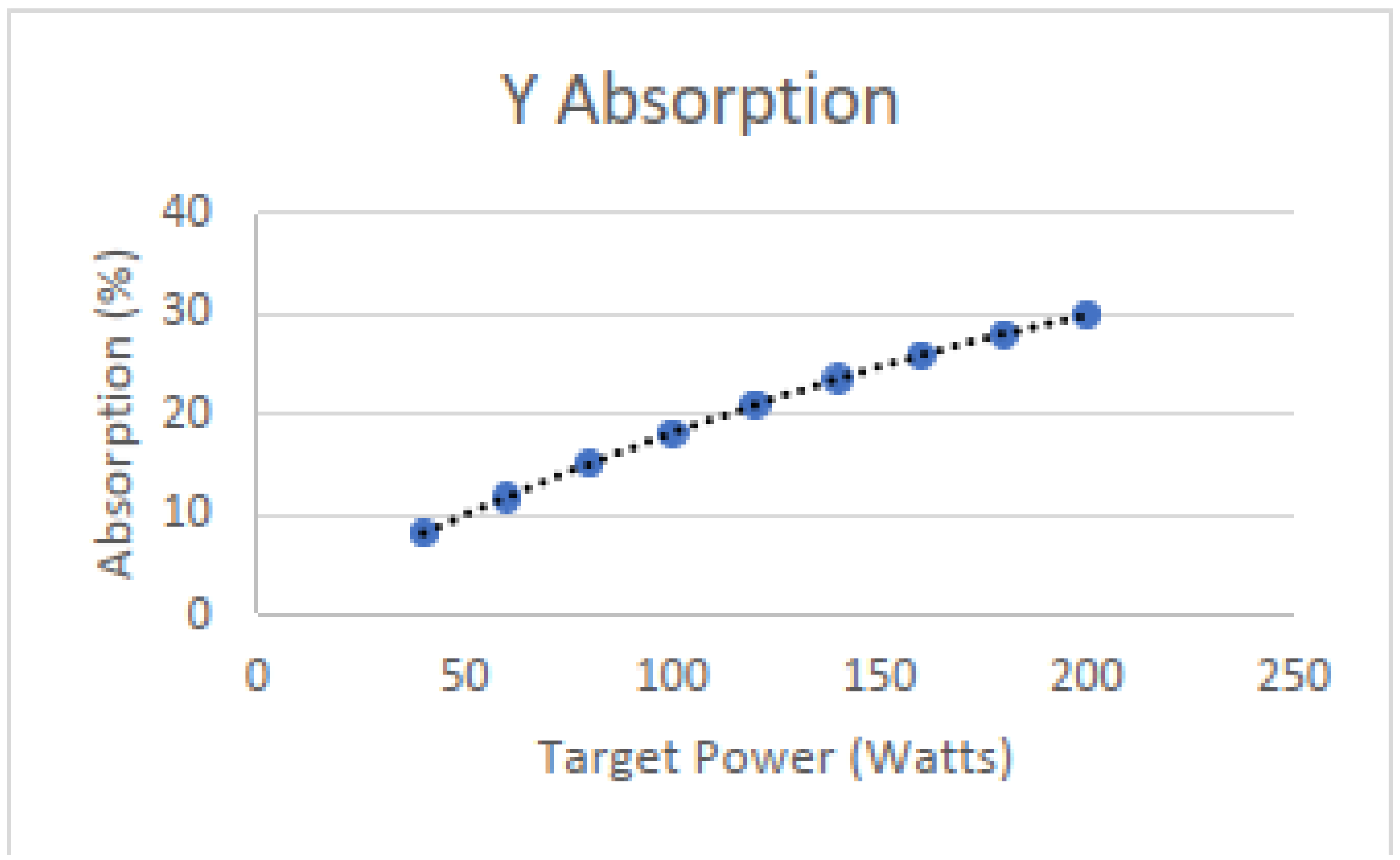
Yttrium and YSZ deposition

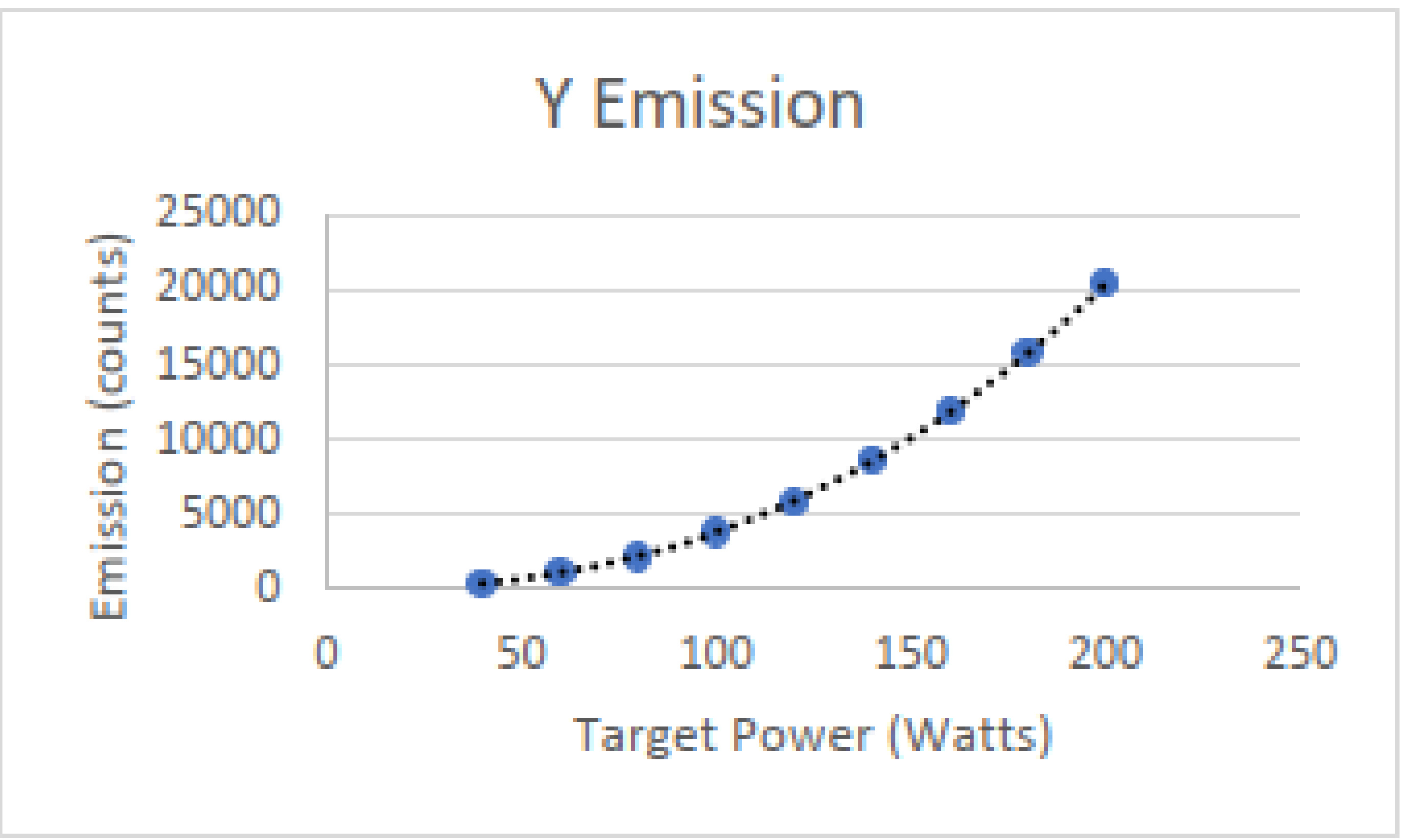




Taking average at platoon and plotting as a function of power

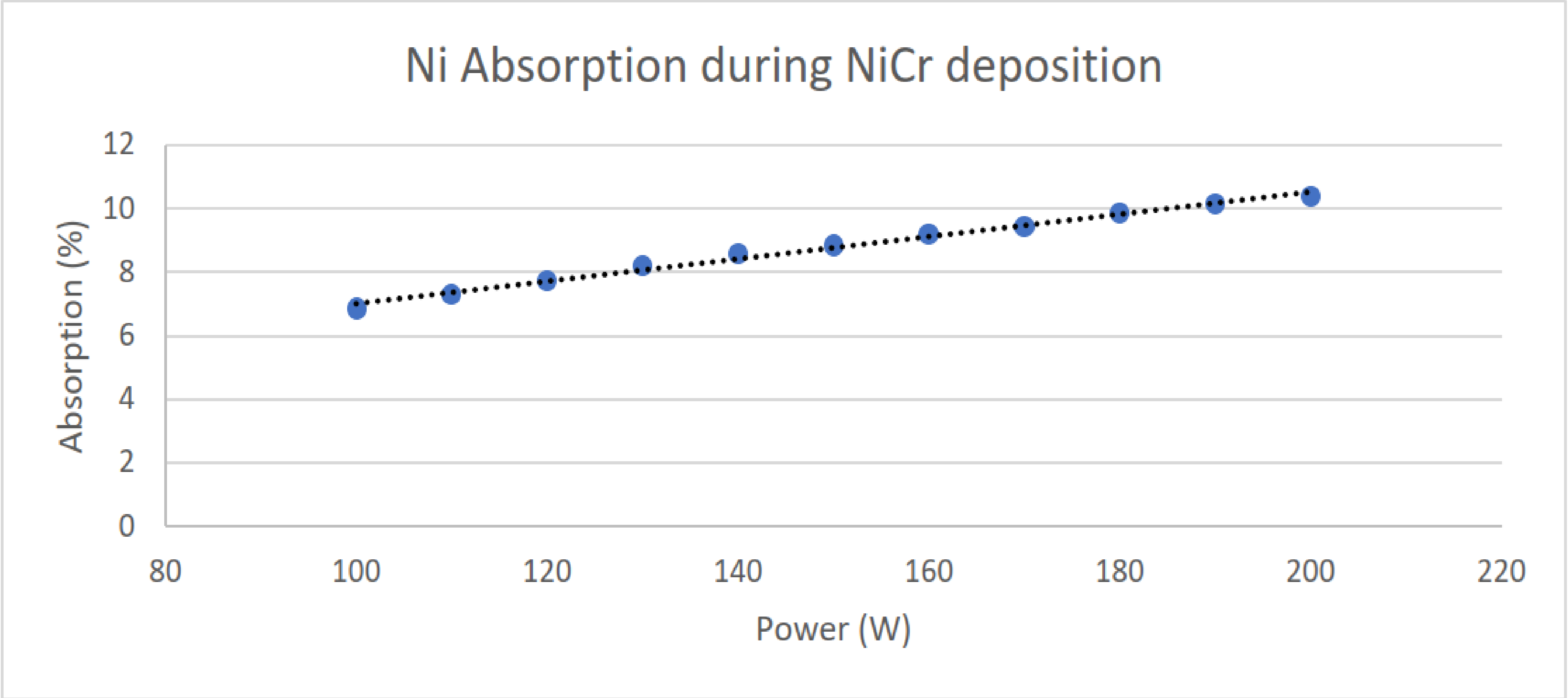
Behavior is not linear, and curvature depends on process/element

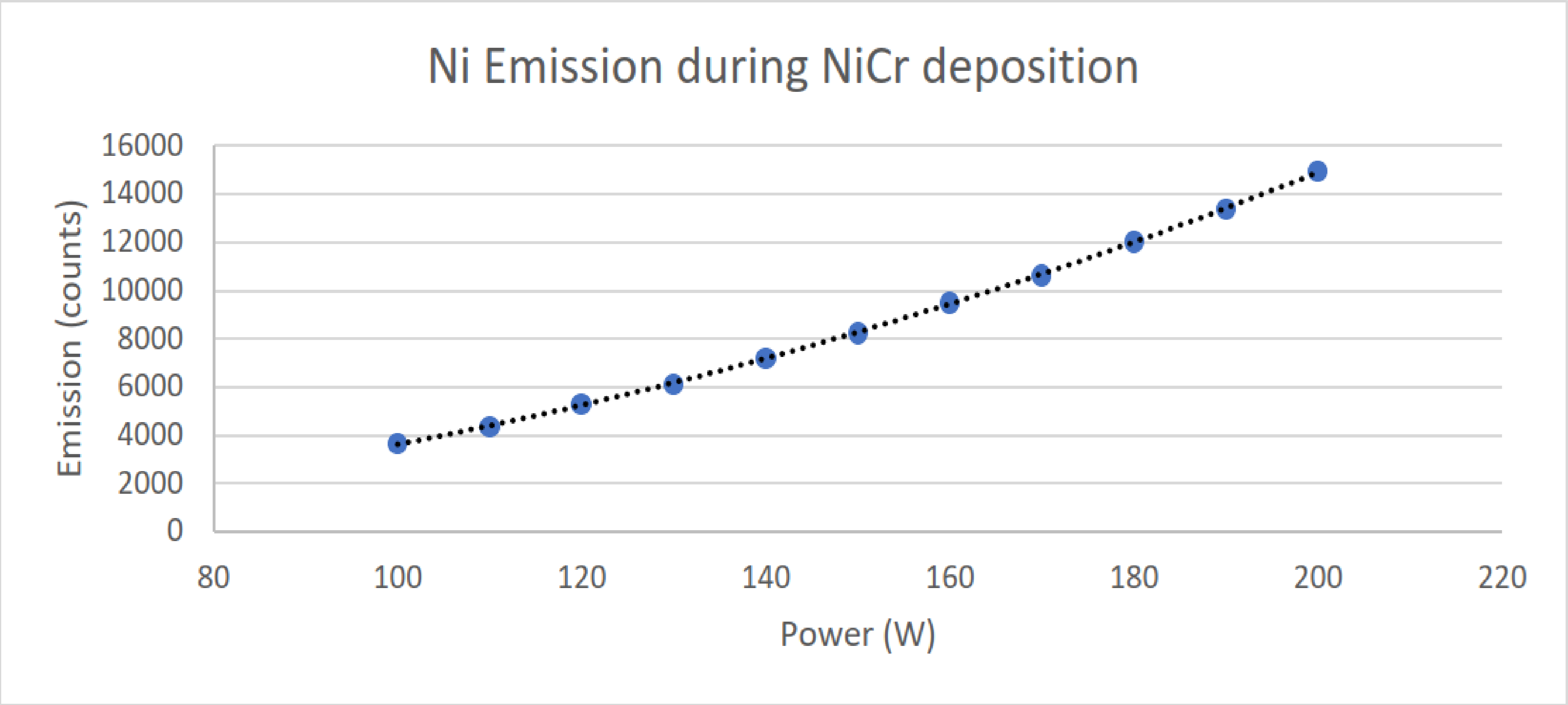




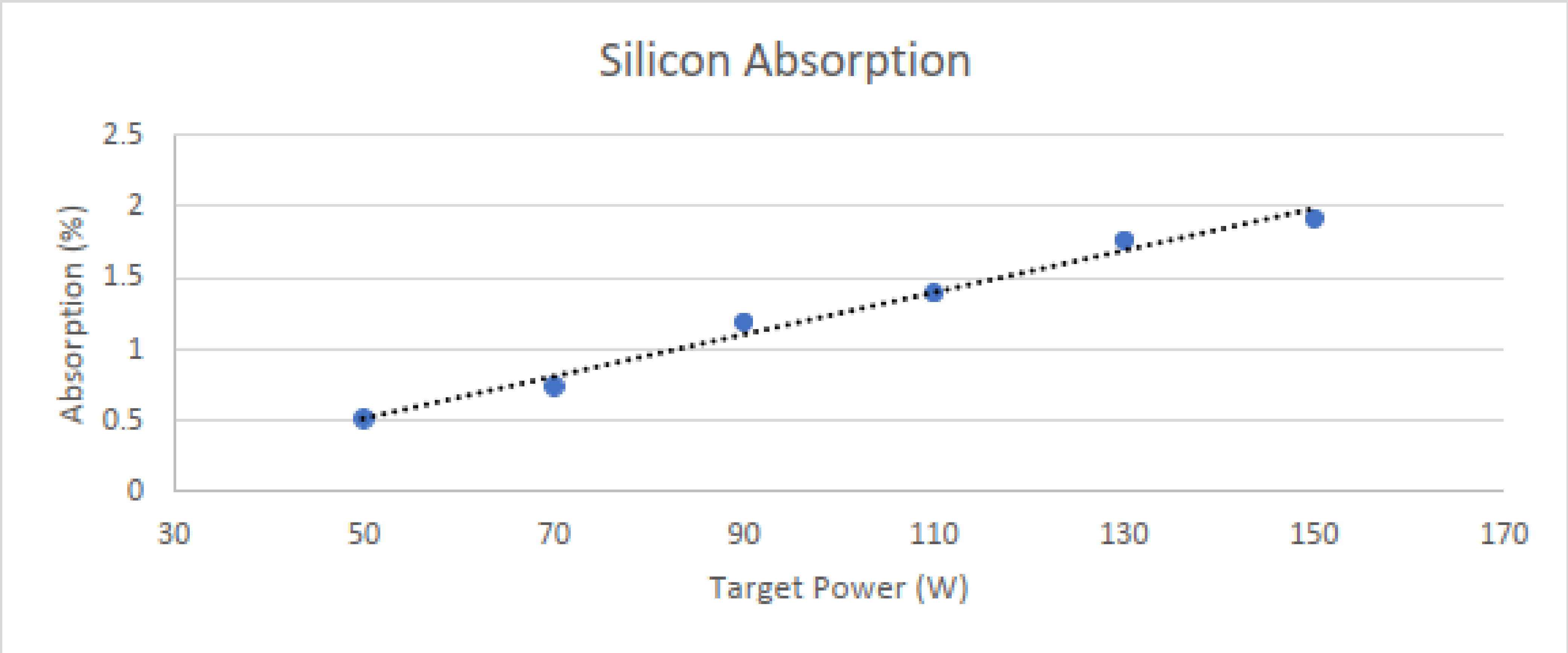
Nickel, NiCr and Si Deposition

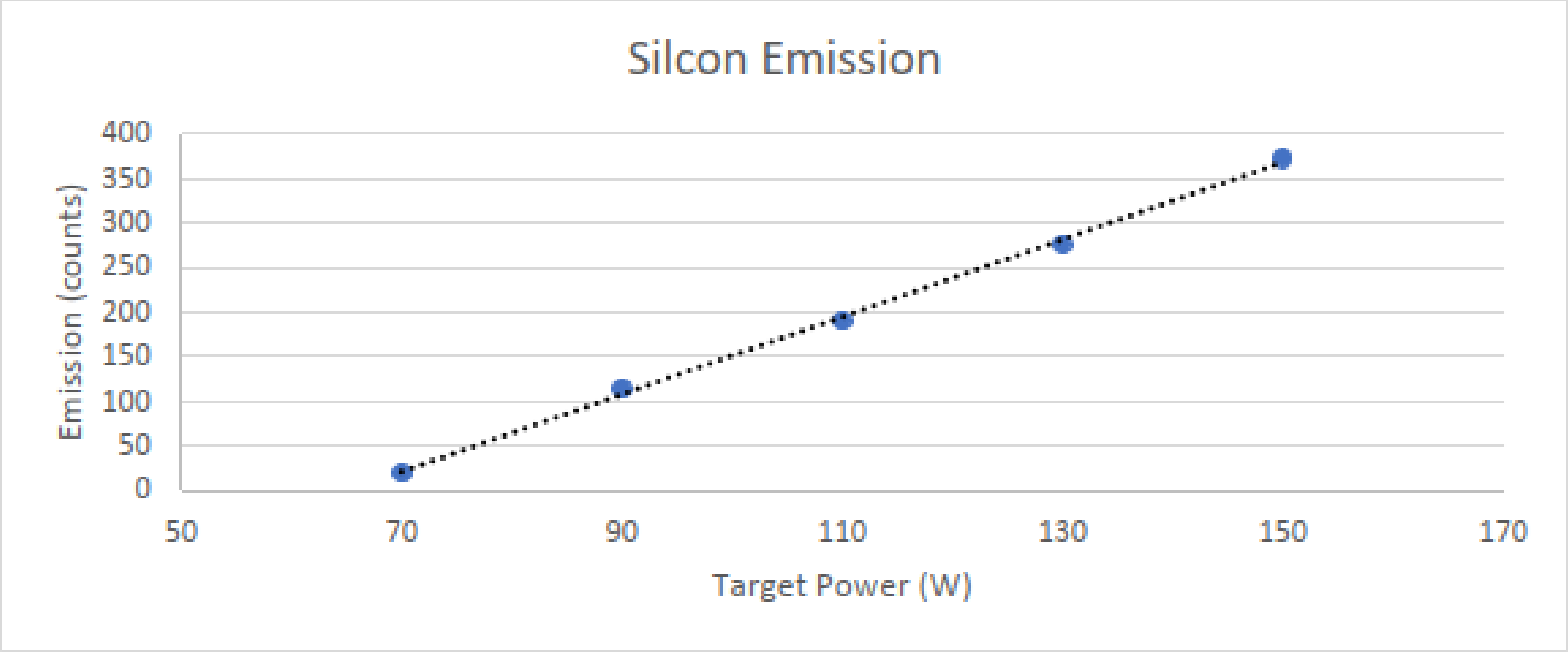
Control of individual elements during deposition of compounds





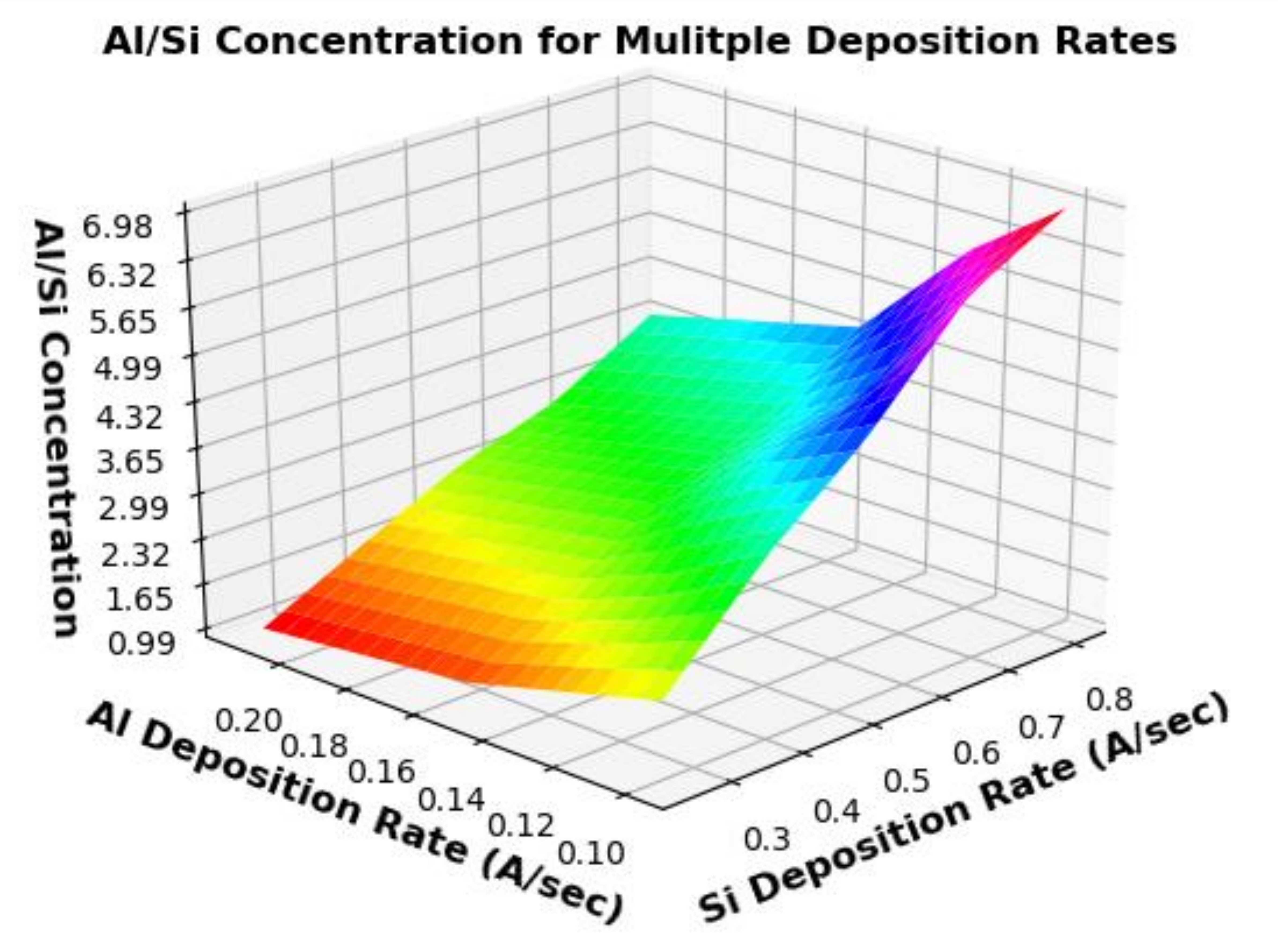
Some elements are more sensitive, less noise than others



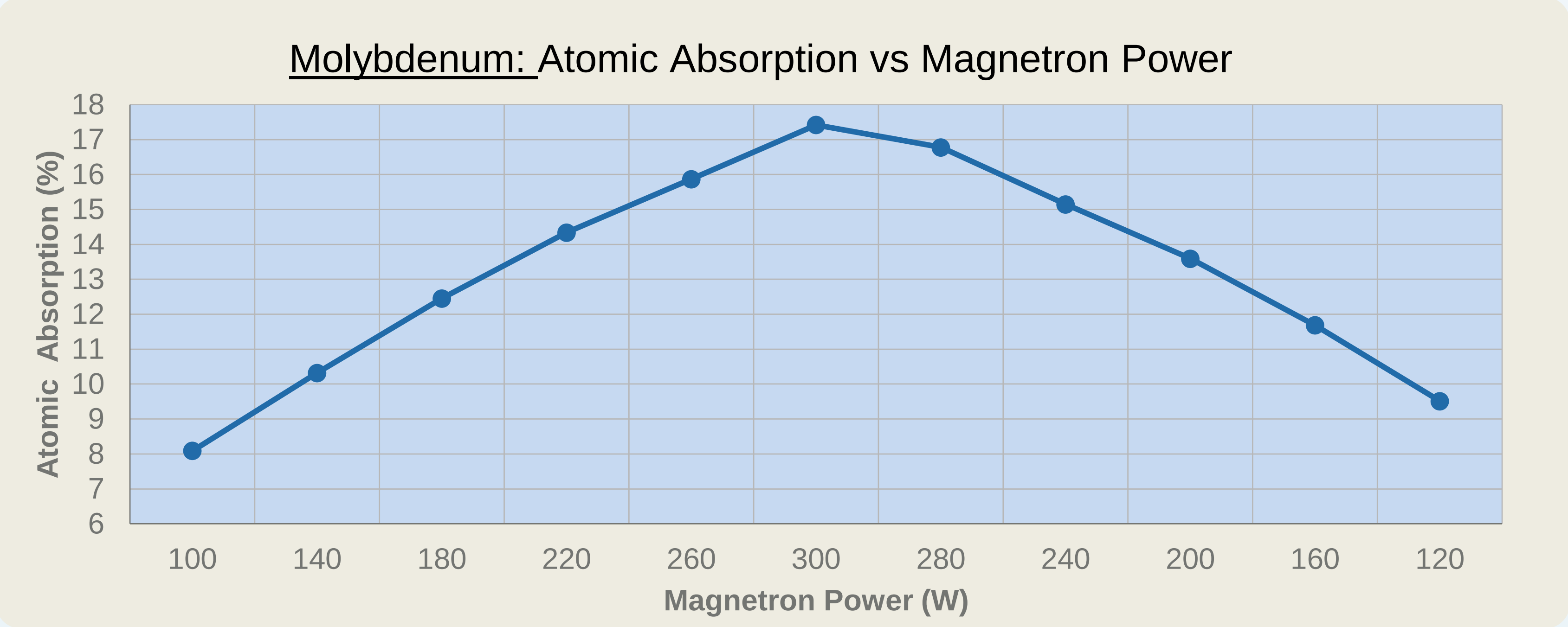


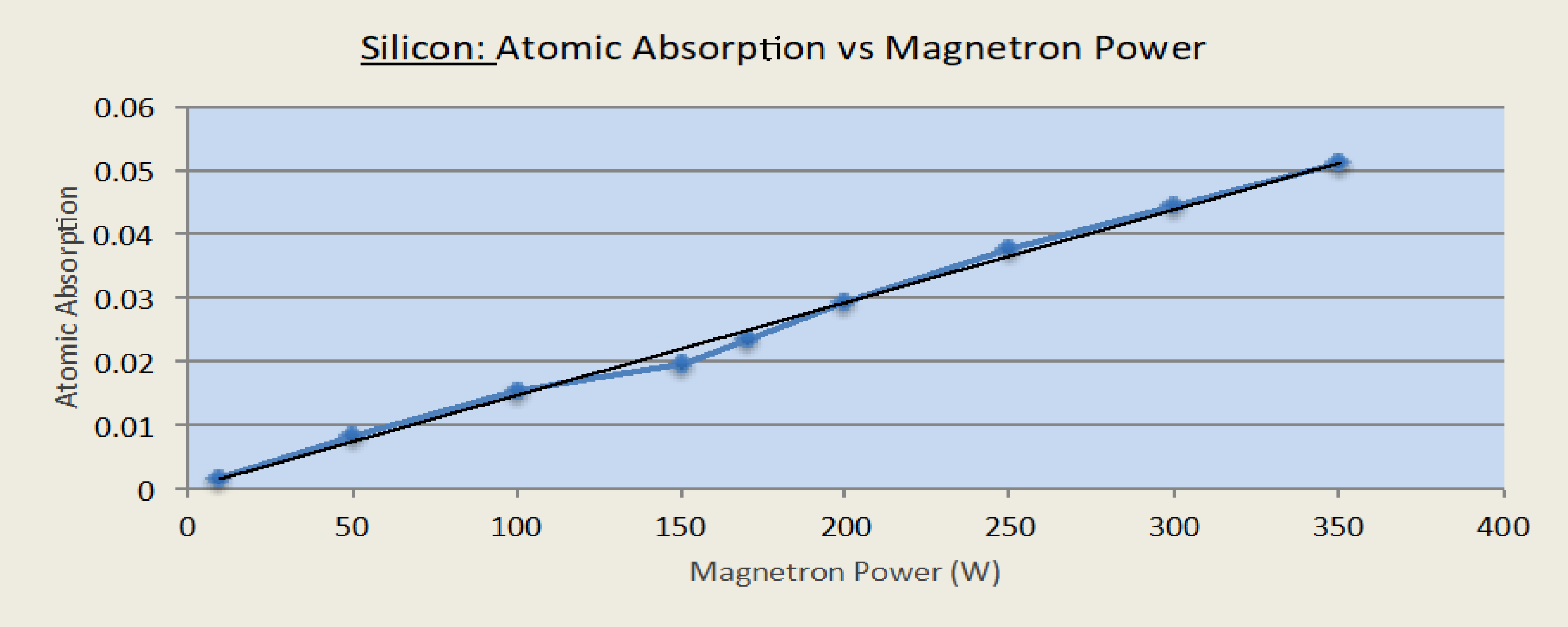
Composition 3D models: example of Al/Si

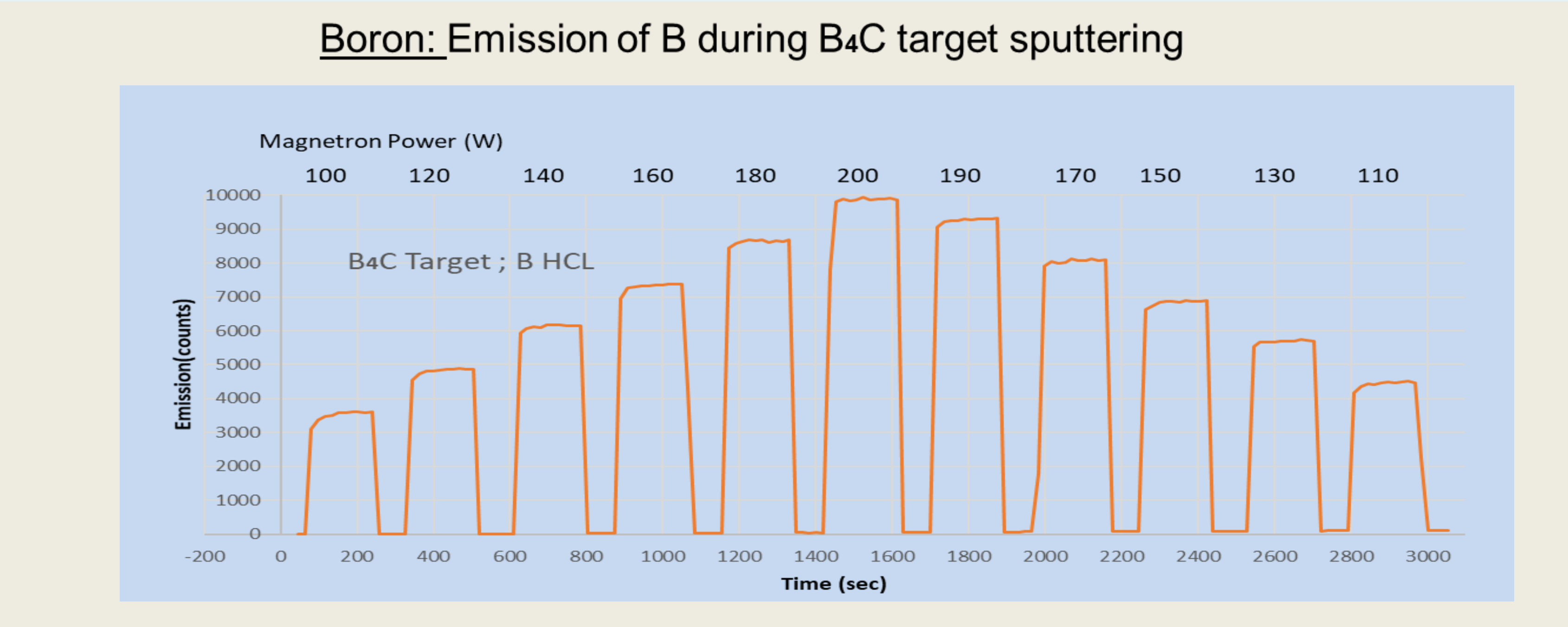
- Co-deposition: each element is monitored individually
- Deposition rate is calculated from atomic concentration of Al-Ni w/o tooling factors
- Individual Si and Al sources are used to adjust the deposition rate independently
- Minimal interference by each of the elements was detected

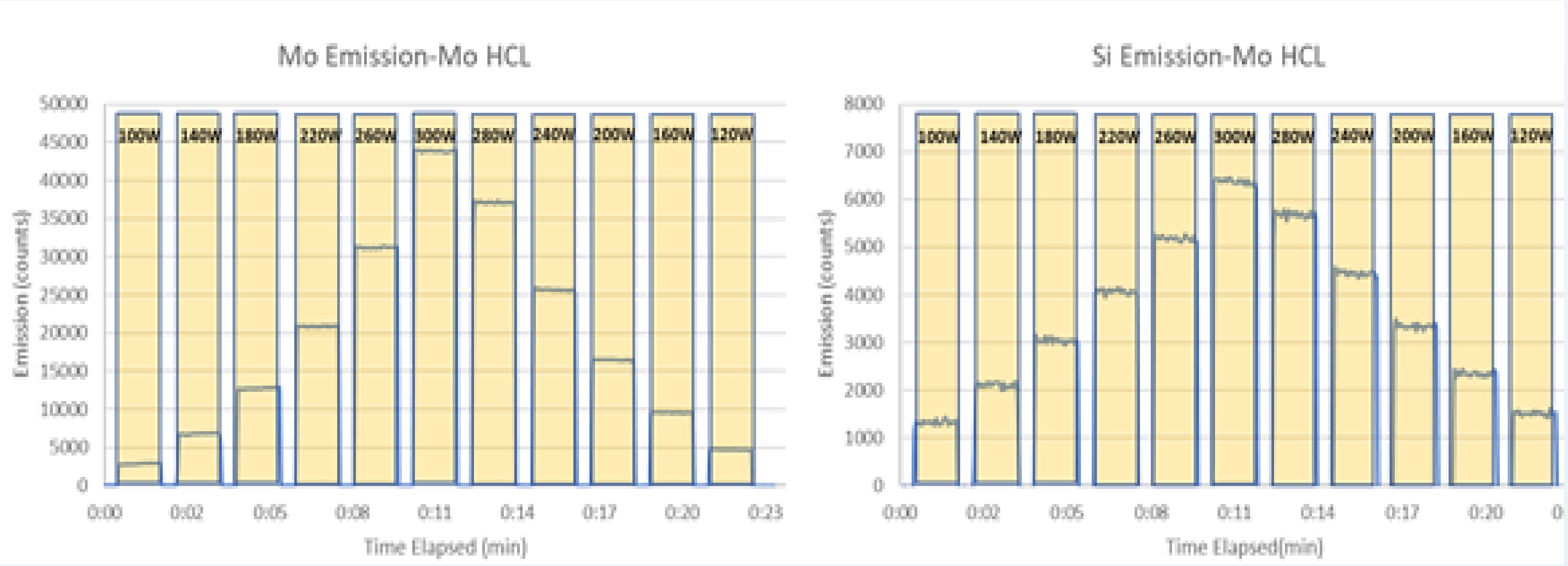


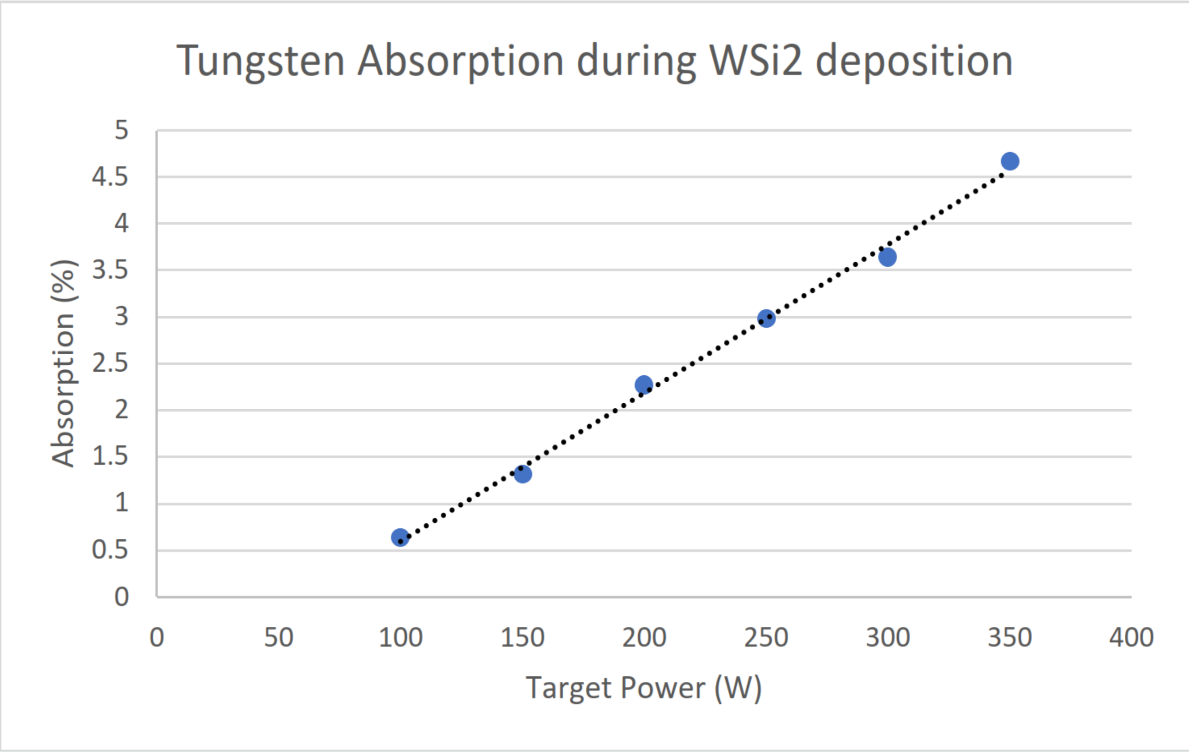
Validation in Real EUVL Thin Film Processes

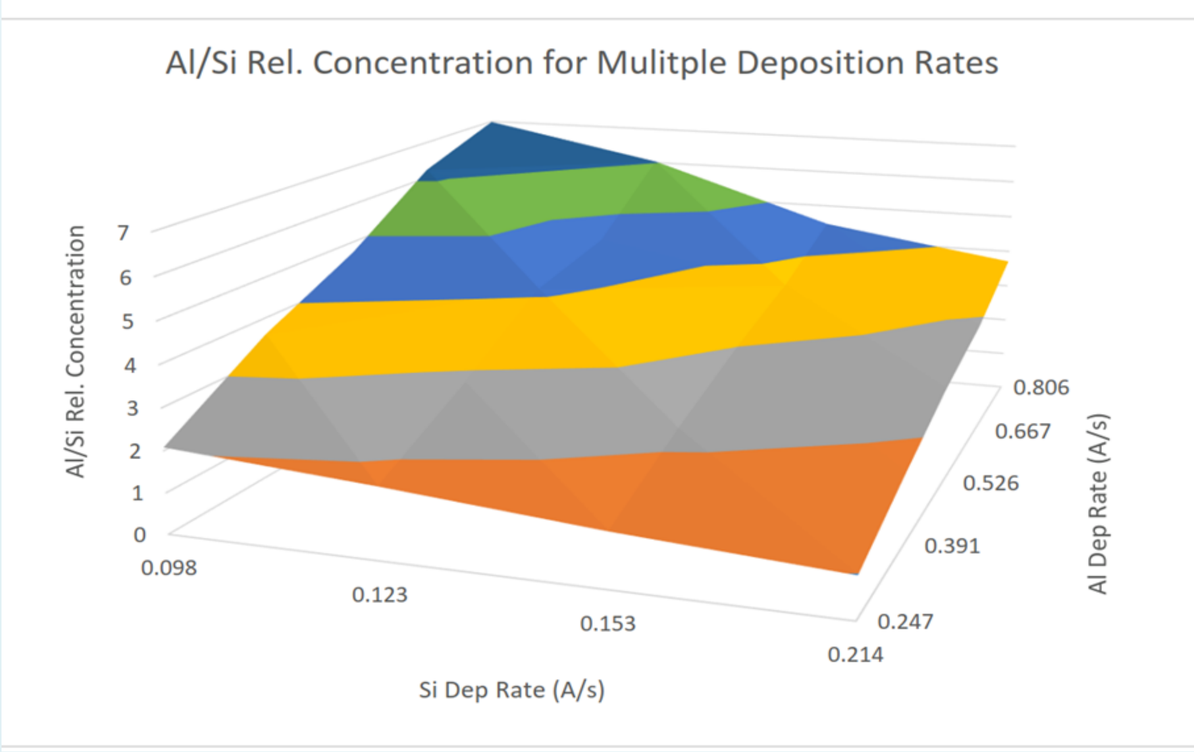






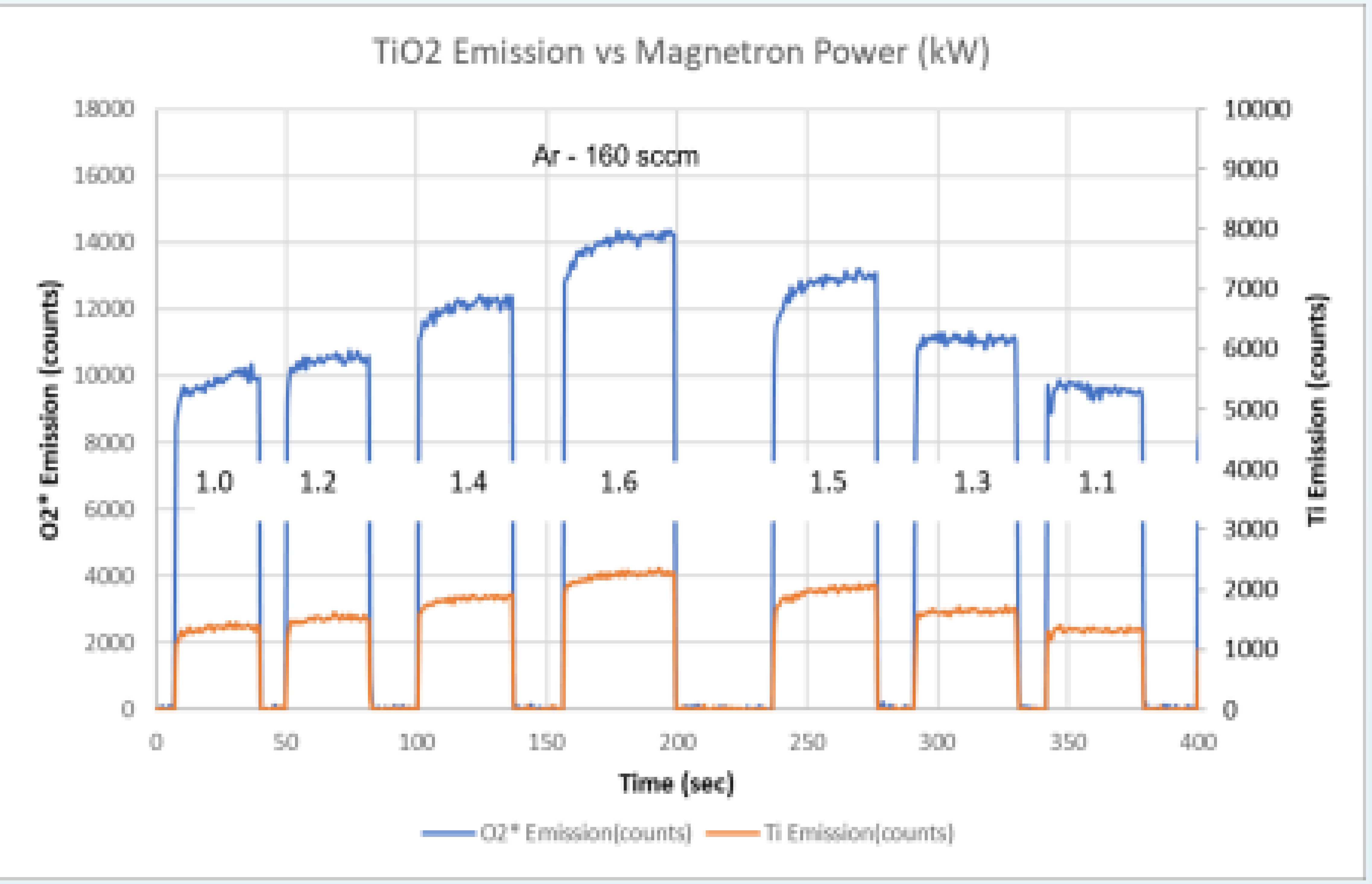






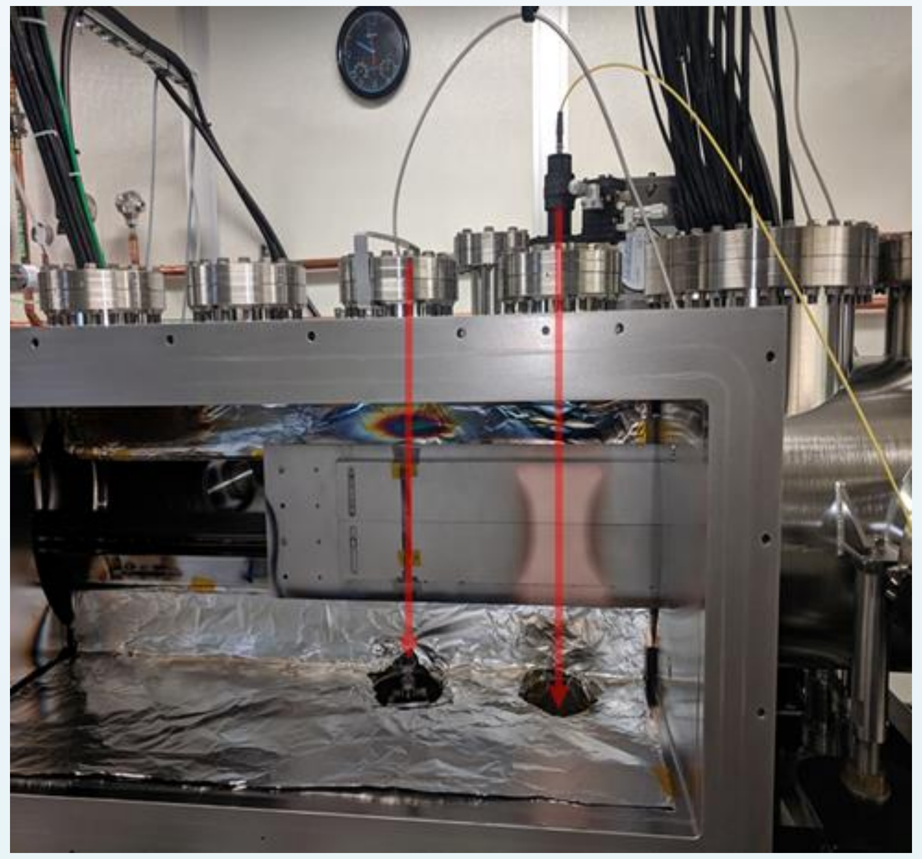
Monitoring reactive processes / oxides

- Sputtering of TiO_2 films with 160 sccm of Ar and 50 sccm O_2
- Magnetron power changed in step-wise function
- Most elements, incl. Ti have 2 or 3 absorption lines in the UV-VIS
- Reactive gases and radicals emit multiple emission lines
- The multiple lines for each an element are used for characterization of energetics of particles
- Machine learning critical for energetics and related composition, structure and morphology

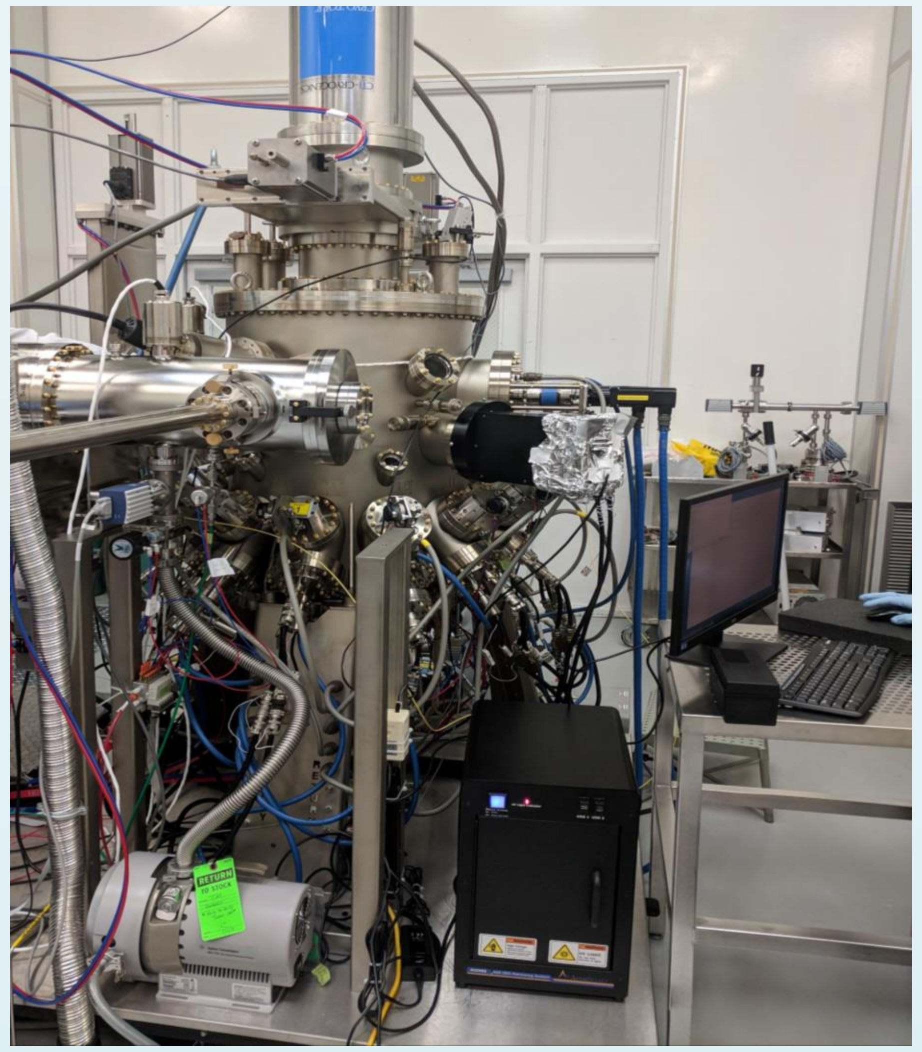


PES is not nearly as stable as AAS

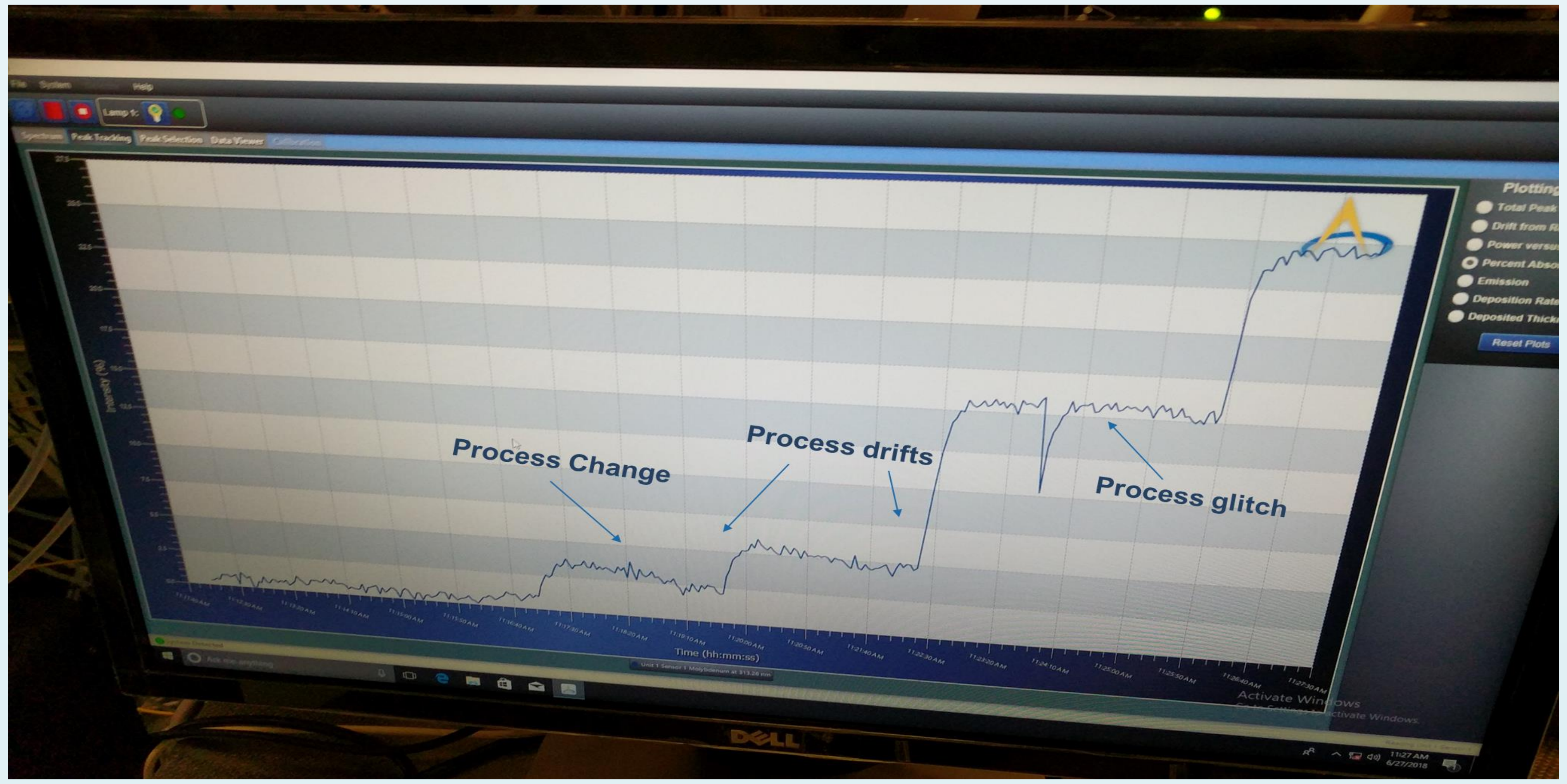
Process failures, drifts and glitch detection



AtOMS system installed in a chamber with translational magnetron movement

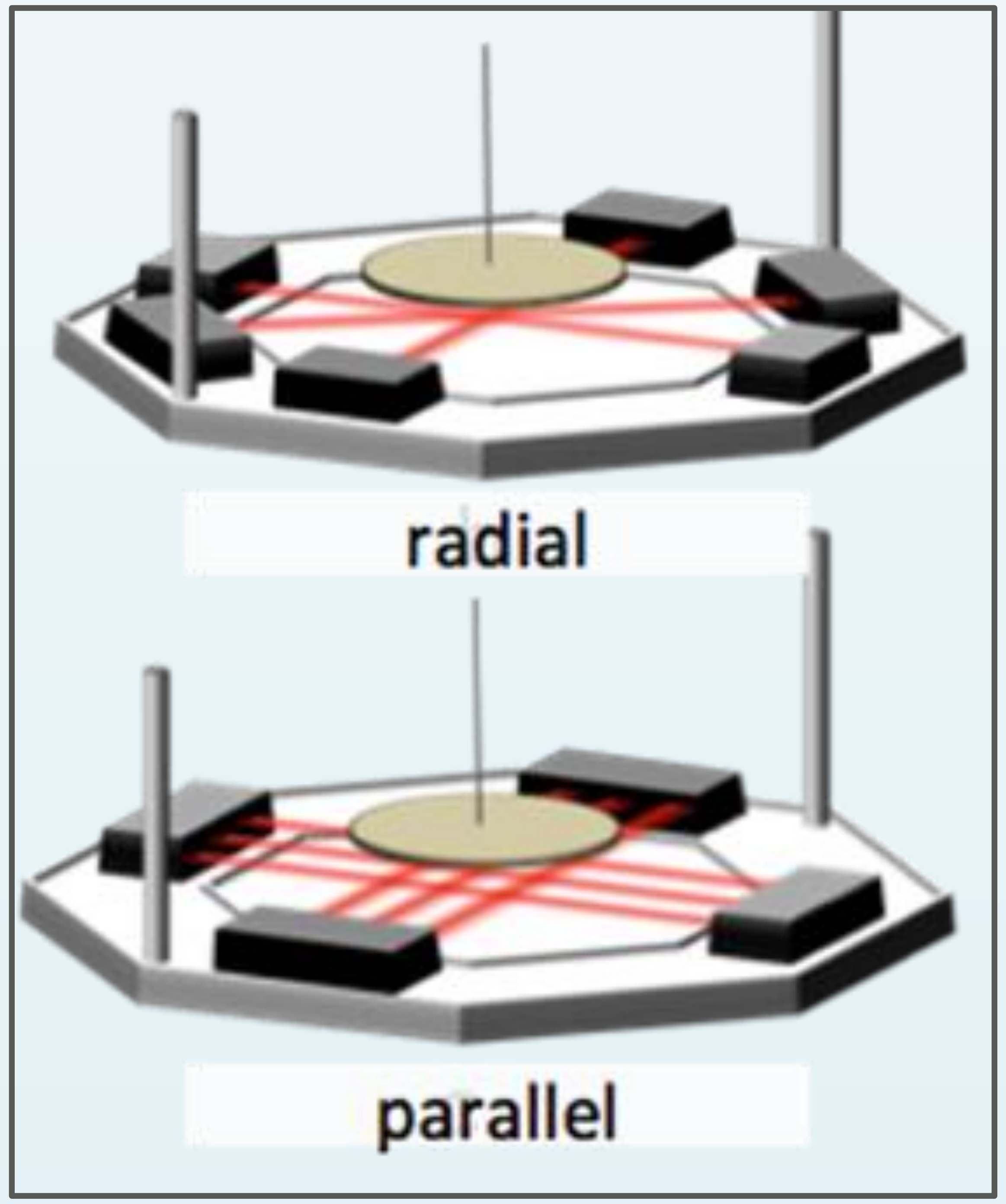


AtOMS system installed in a customer MBE chamber with EB-gun



AtOMS System Capabilities

- Atomic concentration and energetics of elements during multi-element depositions
- Deposition rates of multiple elements simultaneously w/o or little tooling factors
- Etching of very small areas on very large wafers
- Chemical composition and its uniformity of compound films and alloys
- Monitors optically opaque materials, metals and alloys
- >60 individual chemical elements can be monitored
- Multiple chambers and compartments monitored simultaneously
- Distributed monitoring over the wafer area for uniformity control
- Does not intersect with substrate, agnostic to substrate shape and motion
- Control of extremely thin films and interface layers (<3 nm)
- Control of very high deposition/etching rates and total thicknesses
- Deposition/etching rate accuracy - element specific (typical rate ±0.01Å/s)
- Film composition accuracy ±0.05 atomic % (element specific)



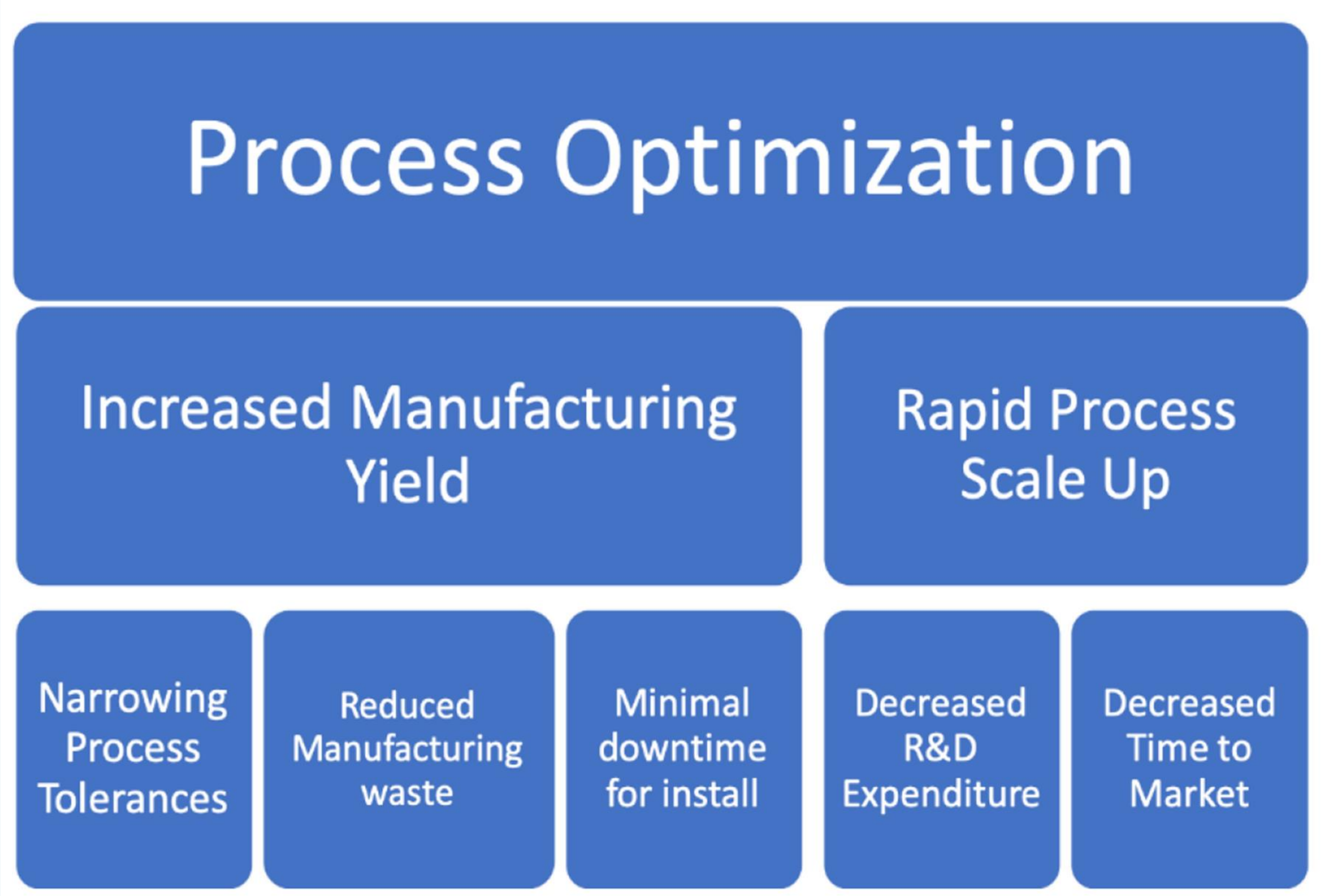
Multiple probe beams trace the deposition plum under substrate

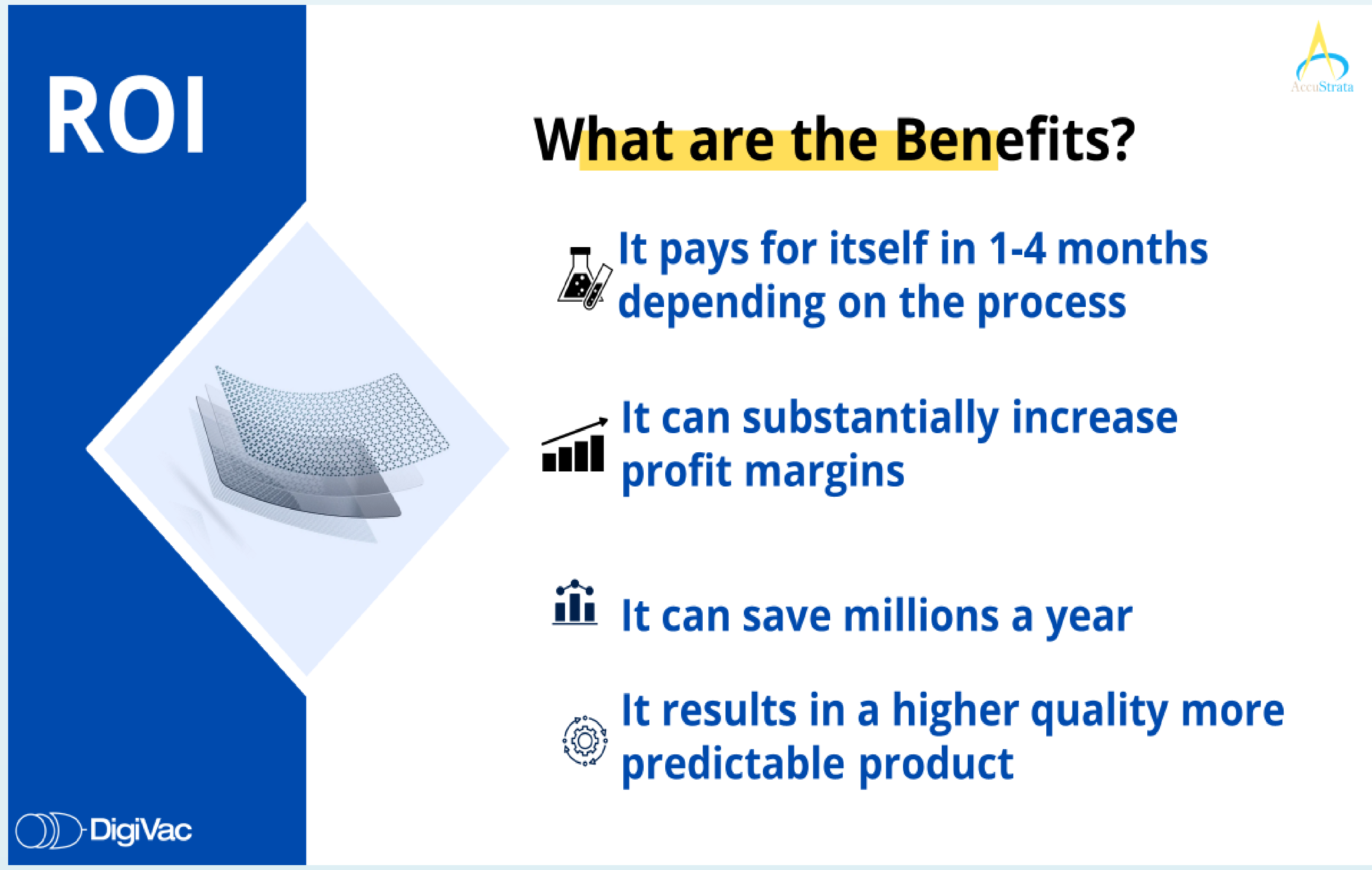
AtOMS validated in manufacturing

- Aluminum and Al/Si
- Silicon
- Cobalt
- Copper
- Molybdenum and Mo/Si
- Gallium
- Titanium
- Tungsten and W/Si
- Yttrium
- Zirconium and YSZ
- Gold
- Indium and In/Ga
- Zinc
- Boron

Over 20 elements, 15 compounds, many oxides, nitrides and B_4C

AtOMS: Technical and business proposition





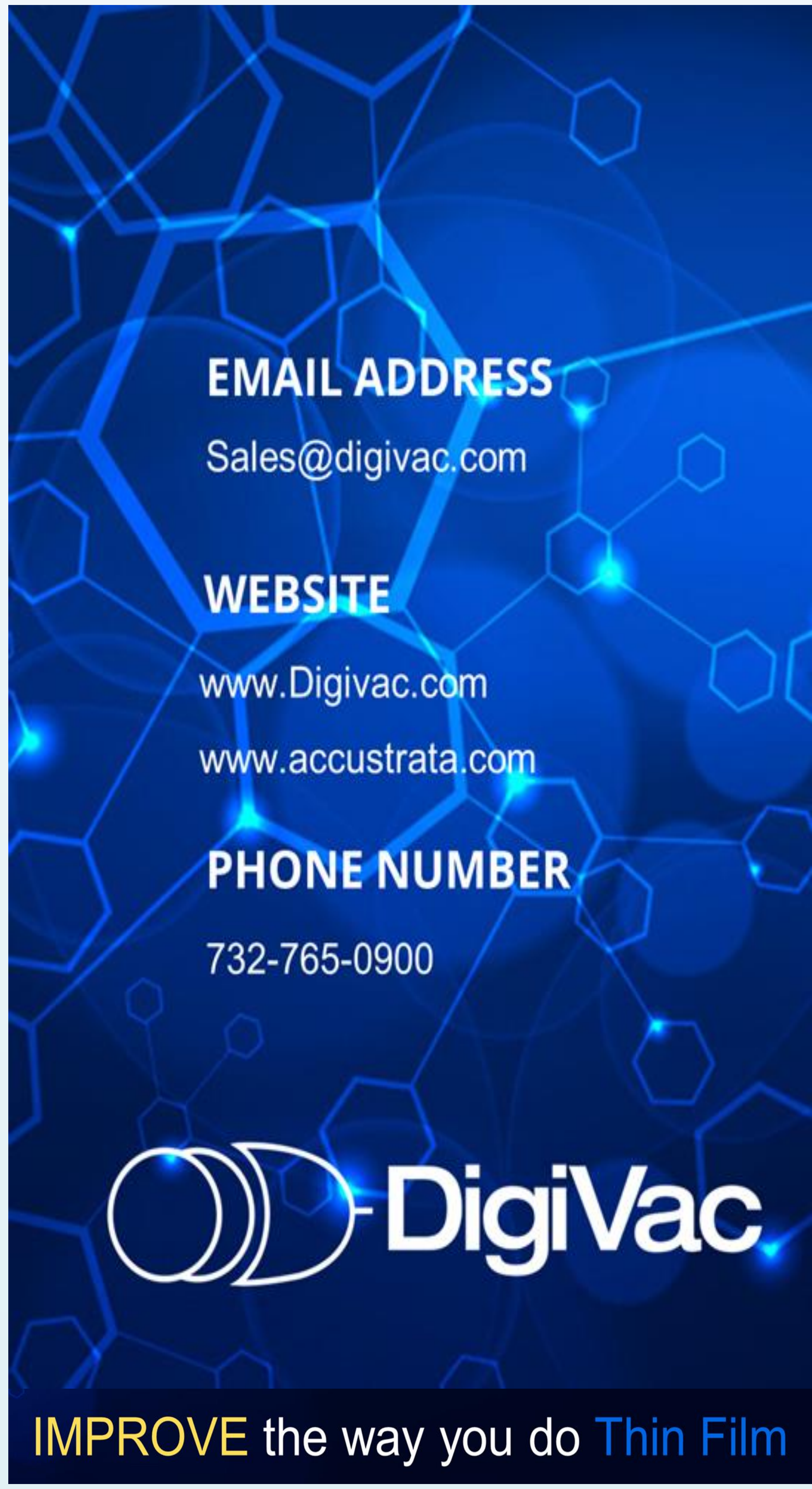
Case Study 1: 6-10 micron thick $LiCoO_2$ thin film battery films

Case Study 2: Ternary and quaternary compounds i.e. AlInGaAs

	PVD co-deposition of $LiCoO_2$			Co-deposition of AlInGaN, AlInGaAs or 3-element c		
		Conventional runs	AtOMS		Conventional runs	AtOMS
Number of runs	run/year	120	120	run/year	220	220
Number of runs for life of AtOMS	run/5 years	600	600		900	900
Cost of the run, labor+FB+material+facility+maintenance	$	18,000	18,283	$	32,000	32,197
Cost of a substrate, incl. preparation $	$	10	10	$	15	15
Number of substrates, 4" diam	# 4"diam	48	48	# 3"diam	64	64
Cost of substrates	$	480	480	$	960	960
Cost of testing/inspection	$	800	800	$	1,800	1,800
Total Direct Cost		19,338	19,621		34,839	35,036
G&A	30%	5,801	5,886	30%	10,452	10,511
TOTAL COST per run	$	**25,139**	**25,508**	$	**45,291**	**45,547**
Cost per subsrate	$	**524**	**531**	$	**708**	**712**
Thickness Uniformity, ~6 micron	%	85	90	%	85	90
Composition Uniformity	%	80	95	%	75	90
Composition Depth Profile Homogeneity	%	75	85	%	75	88
Compound Manufacturing Yield	%	**51.00%**	**72.68%**	%	**47.81%**	**71.28%**
				Diced LED Chips 2x2 mm^2 per 3" sapphire wafer ~7		
Price of GOOD product	$/substrate	995	995	$/substrate	1,620	1,620
Substrates sold at 100% price	per run	24.5	34.9	#/bin	30.6	45.6
Siubstrates sold at 80% price	per run	9.6	9.6	#/bin	9.6	9.6
Rejected substrates		13.9	3.5		23.8	8.8
Revenue per successful run	$	31,999	42,351	$	62,014	86,345
Rejected runs for other reasons	%	7	7	%	10	10
Adjusted revenue	$/run	**29,759**	**39,387**	$/run	**55,812**	**77,710**
Profit	%	**15.5%**	**35.2%**	%	**18.9%**	**41.4%**
Cost of AtOMS at purchase	$		**145,000**	$		**145,000**
Cost of AtOMS over 5 years	$		**29,000**	$		**29,000**
Service contract	$/year		**25,000**	$/year		**25,000**
Part and maintenance	$/year		**7,500**	$/year		**7,500**
Total cost of AtOMS for 5 years	$/year		**300,000**	$/year		**300,000**
ROI, number of runs	runs		**29**	runs		**12**
ROI, number of months	months		**3.0**	months		**1.3**
Saving per year for 100 runs/y	$/year		**1,037,911**	$/year		**2,407,316**

Summary

- **AccuStrata offers a best-of-breed capability for next generation quality monitoring and process control**
- **Technology allows *in situ* monitoring and control of composition of compound materials and alloys and film quality during thin film manufacturing**
- **Provides monitoring and control capabilities that have previously been available "post-fab" only (i.e. once manufacturing is complete)**



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