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# Reactive Magnetron Sputtering Feedback Control, ‘Flexibility for Success’

**Joseph Brindley, Benoit Daniel, Victor Bellido-Gonzalez, Dermot Monaghan**
Gencoa Limited, Liverpool, United Kingdom

Developments in reactive magnetron sputtering processes have unlocked great possibilities in controlling film stoichiometry and physical properties. For some material/reactive gas combinations, it is crucial that the reactive gas flow is regulated via a closed-loop feedback system, able to capture the system status and adjust the reactive gas input at any given time. In this context, the deposition of consistent and reproducible film properties relies as well on the selection of one or more quick responding sensors that can provide relevant information on the nature of the material being deposited. Examples of these sensors include direct plasma measurements, such as plasma emission intensities, electron temperature and plasma frequencies, or indirect system measurements, such as reactive gas partial pressure and sputtering target voltage. Having the flexibility to choose a sensor that will enable the best cost to performance formula is a primary concern.
In this work we present a new feedback control platform to sense and control any form of reactive sputtering process. The system can use up to 16 different sensor inputs and outputs in a ‘plug and play’ arrangement. Despite the high number of simultaneous control loops, the speed of signal acquisition to gas value ‘feedback’ is within 1 msec. The flexibility to easily ‘switch’ sensor type to enact the process feedback control, allows the optimum solution to be arrived at as quickly as possible and at the lowest cost. The sensor types available vary from:

- ‘In-situ’ or ‘remote’ plasma emission via either a standard or high sensitivity HS spectrometer,
- 'In-situ' or ‘remote’ plasma emission via an optical narrow bandpass filter and photomultiplier,
- Sputter target voltage from the magnetron source power supply, and
- Partial pressure signal of oxygen from a Lambda type of process sensor.

Typically, an optimum control strategy might require multiple sensor signals to be combined as the input to the feedback control algorithm controlling a reactive sputtering zone. This signal ratioing can be performed within a msec based upon the new control architecture. Whilst the system sensing and control hardware is more sophisticated, a built-in auto tuner ensures simple operator interface. The process control benefits of this new control platform for reactive sputtering will be presented.

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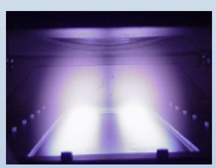
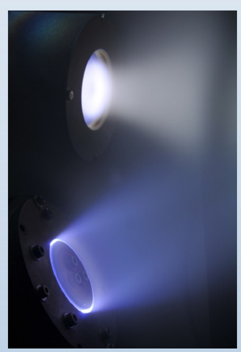
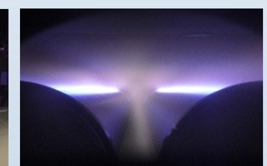





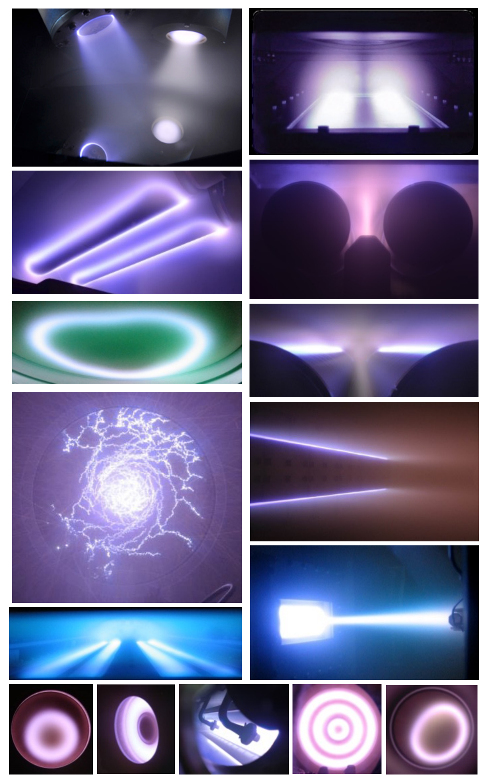

# Reactive Magnetron Sputtering Feedback Control, ‘Flexibility for Success’

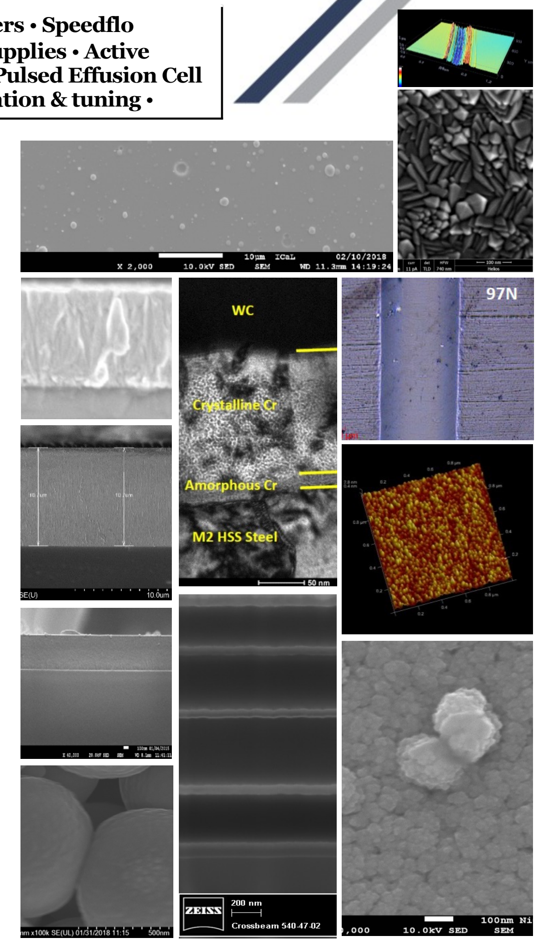
Structure of talk:

- Hysteresis behaviour
- Why choose feedback control
- What sensors to use
- What controller choice
- Conclusions

# Gencoa 30 years experience creating products to create thin films in vacuum

**Rotatable & Planar Magnetron Sputter Cathodes • Retrofit magnetic packs • Plasma Treaters • Speedflo Reactive Gas Controllers • IM Ion Sources & power supplies • Arc MAX sources & power supplies • Active Anodes and Gas Delivery Bars • OPTIX Gas and Chemical Sensing • S and Se Sensor • PEC Pulsed Effusion Cell • V+DLC - Transparent DLC • IC Nano antimicrobial layer technology • Process implementation & tuning •**

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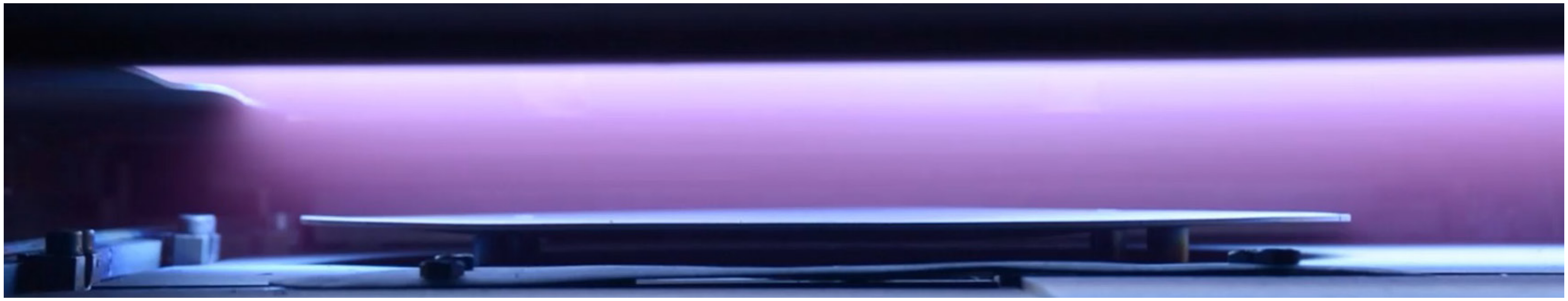
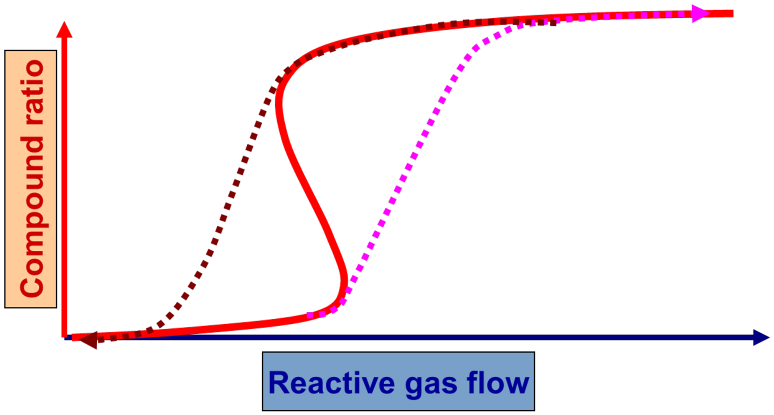
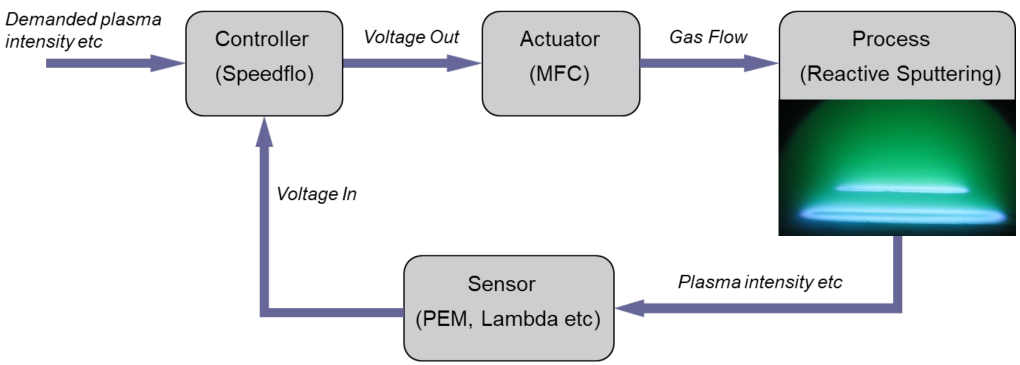


# Control of reactive sputtering processes – Hysteresis problem

Traditional view of S-curve / Hysteresis response.

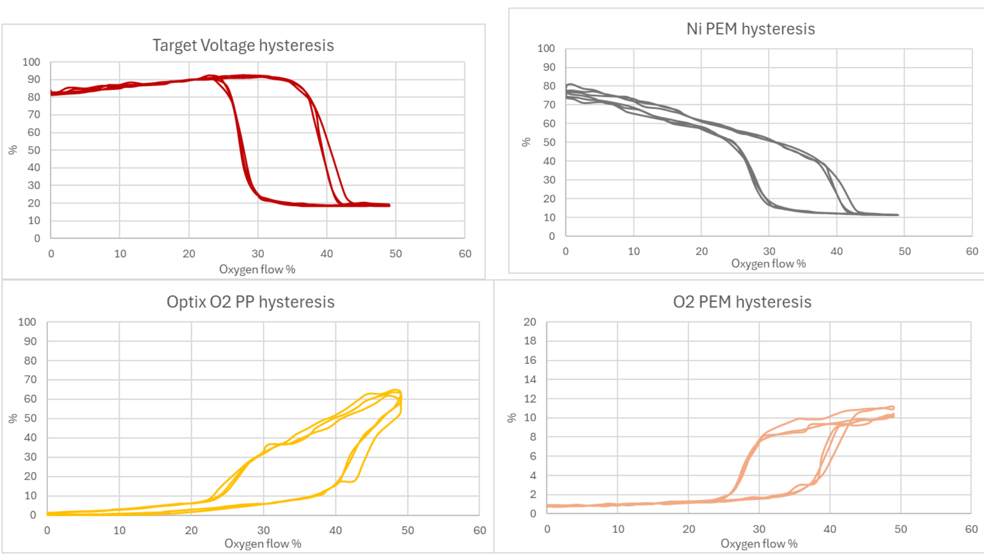


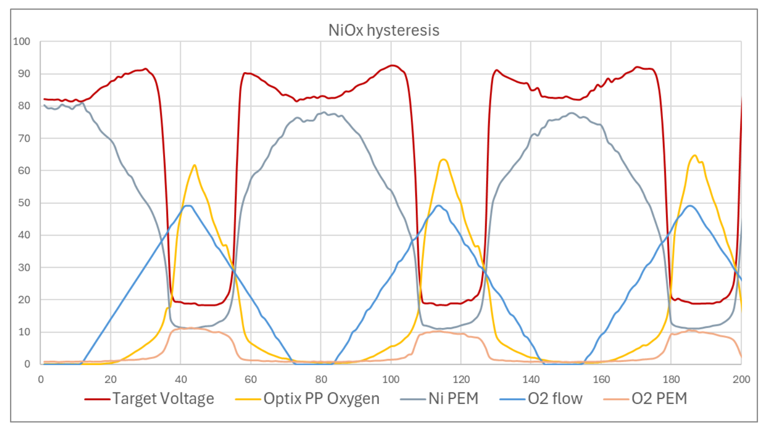



# A closed-loop fast feedback control system can eliminate the ‘hysteresis’ problem

- First start by selecting the most appropriate type of process sensor
- The sensor has to provide a relevant signal from to process to the controller
- Various sensors exist, but the most suitable choice depends upon; budget, the target and gas species present as well as in-process disturbances and system ‘scale’

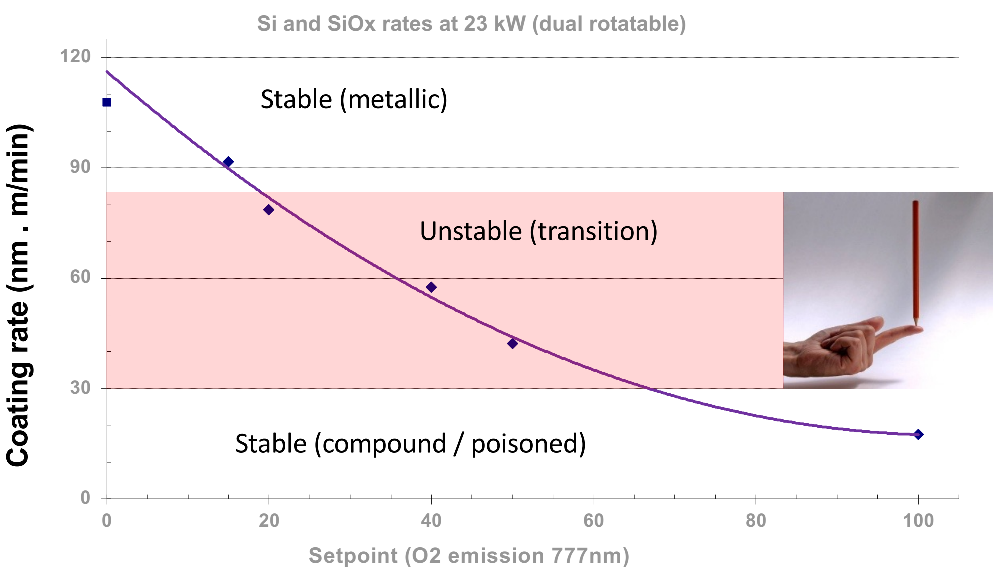
**By performing a gas ramp up and down, the response of  the process can be seeen**



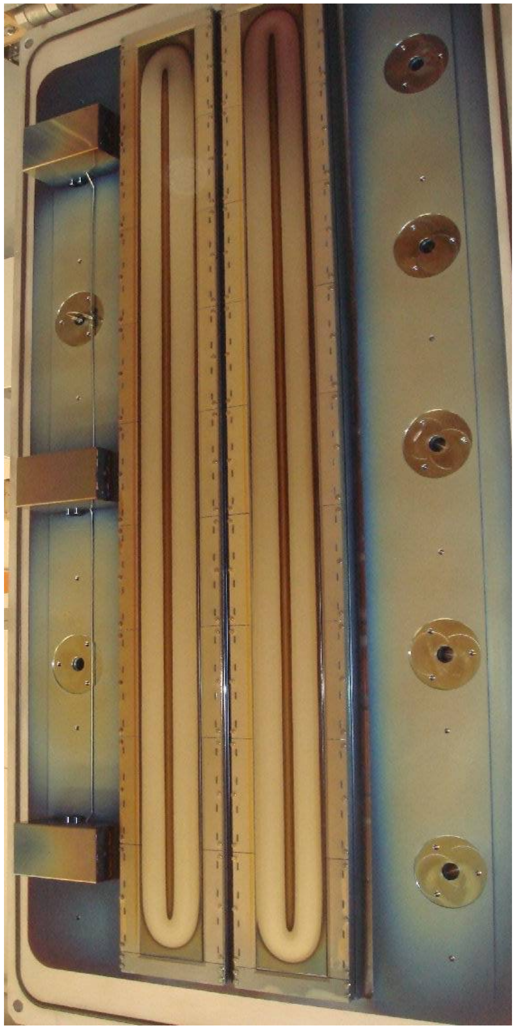



# Why adopt closed loop feedback control for reactive sputtering?

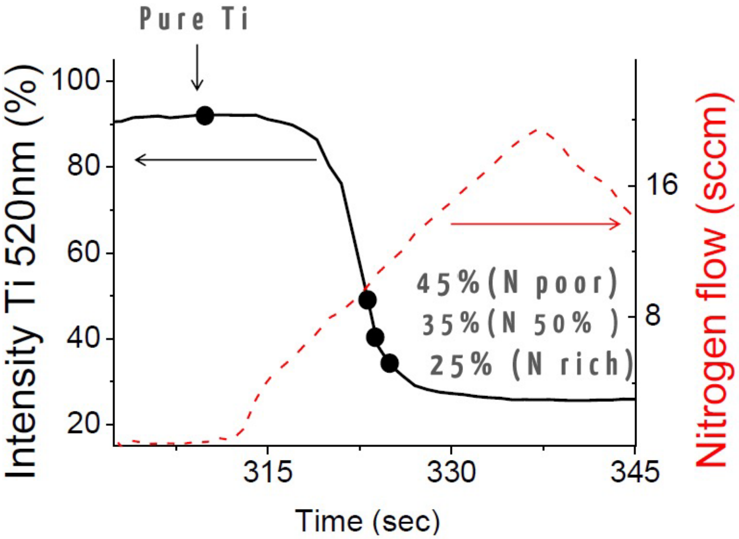
## Enables processes to run 2-3 times faster hence reducing costs and improving productivity




Running in poisoned mode yields low deposition rates.
However, the transition region is unstable – will tend to poison.



# Also closed loop control will deliver more repeatable results eg colour or layer properties





Direct magnetron observation with SpeedFlo CCD

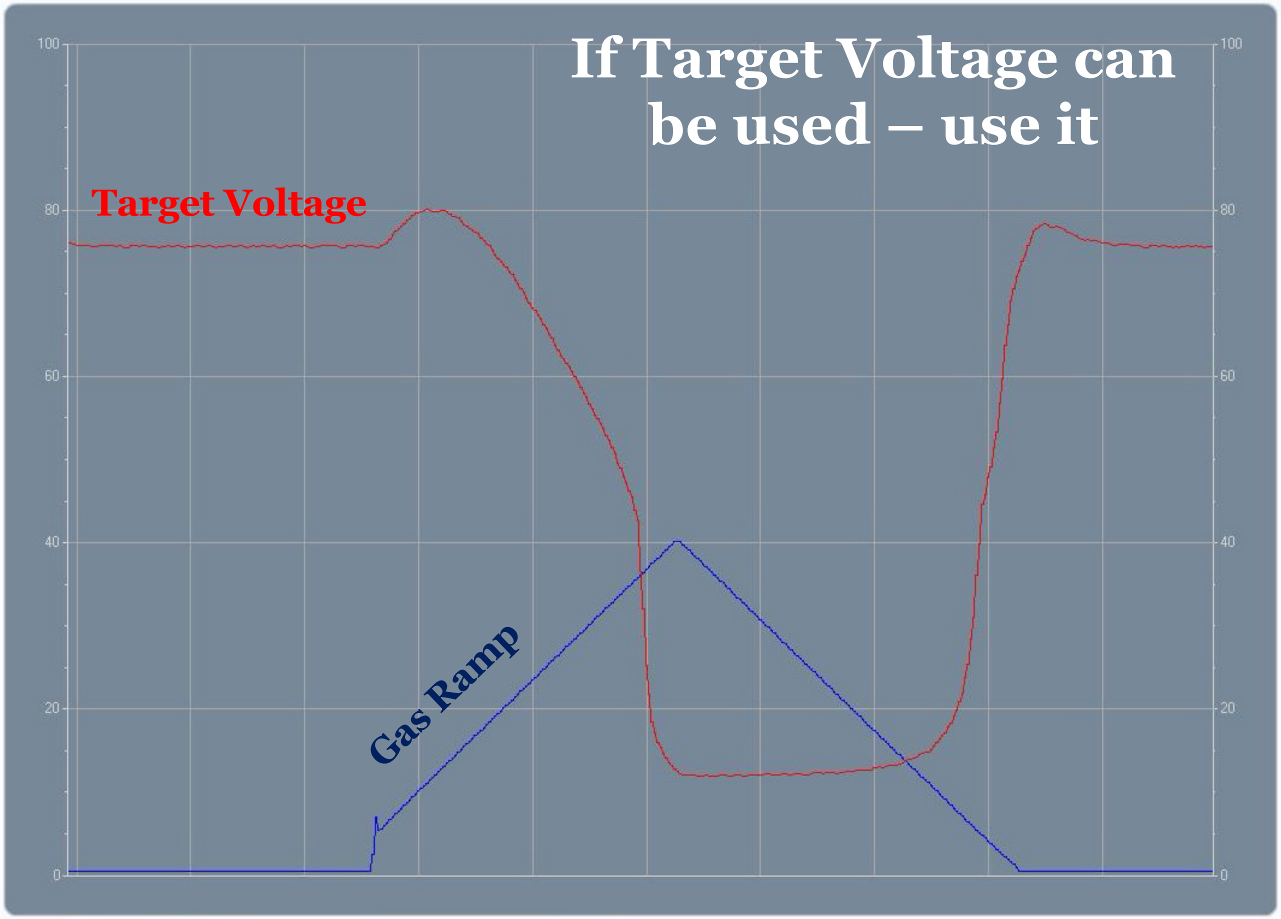
nano4ENERGY

# What are the in-situ and ex-situ sensor options

| | |
|---|---|
| In-situ means sensing the process area directly – receiving a signal from the target or chemistry within the process space | In-situ sensors are;<br>• Target voltage signal<br>• Plasma emission from the sputter target plasma region connected by fibre optic cable to a Photomultiplier Tube (PMT) and Narrow Bandpass Filter (NBF - filter can be configured for either the target species or the gas species).<br>• Plasma emission from the sputter target plasma region connected by fibre optic cable to a spectrometer (can monitor all gas and target species present) |
| Ex-situ means sensing the process indirectly – receiving a gas signal remotely via a sensor on the chamber wall | Ex-situ sensors are;<br>• Remote Oxygen Gas Signal from a VACGAS G16 Lambda type of sensor<br>• Remote gas signal from an OPTIX plasma head connected via fibre-optic cable to a PMT and NBF.<br>• Remote plasma emission gas signal via a spectrometer – OPTIX device with electronic connection to Speedflo controller |

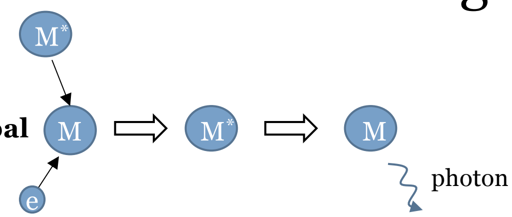
# Target Voltage as a Sensor

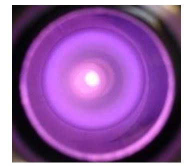
- If the target voltage is transferred from the magnetron power supply via a direct analogue output it is very high speed
- Only cost is a 'cable'
- Ideal signal, but requires a linear change in target voltage with gas flow
- So most successful with silicon and aluminium
- Cannot be used for zone control



# Light emission in plasma to sense species present – can be gas or sputtered metals, known as Plasma Emission Monitoring P.E.M

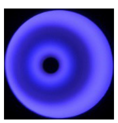
**Excitation principal**

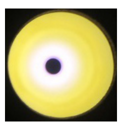


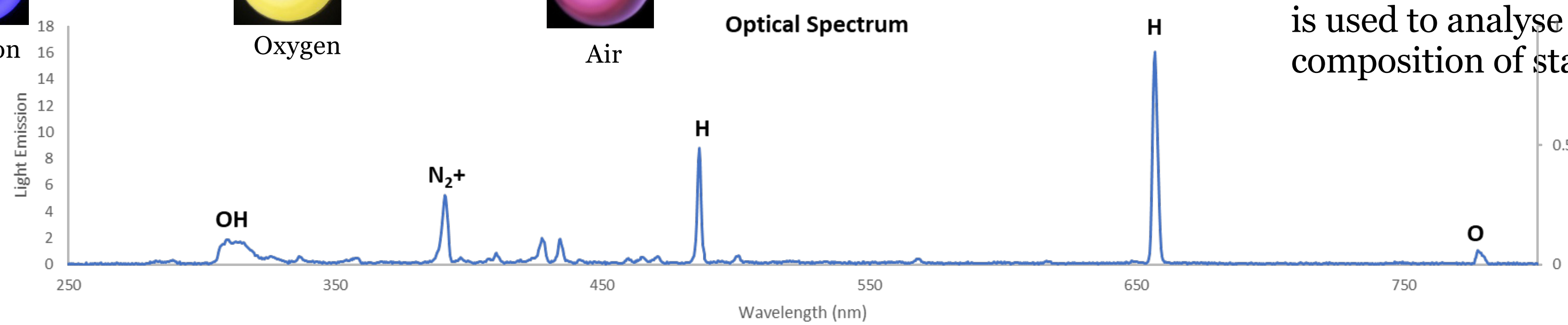
- Quantum mechanics: discrete, allowed excitation states for each molecule / atom
- Energy change between states = wavelength of light emitted = signature for each gas

**Different gases in plasma emit different "colours"**


Argon


Oxygen


Air




The same technique is used to analyse the composition of stars

# How to use plasma light as a process sensor

**Light from the process or remote plasma is transferred via an optical fibre or lens into a light detector**

There are two typical forms of light detector:

- A narrow bandpass filter (NBF) and photomultiplier tube (PMT) – converts a specific wavelength of light intensity into a voltage

- An optical spectrometer which monitors all the visible light emissions present from 250 to 850nm with an intensity output for any species

# Pro's and Con's of light detectors

**Important aspects from a process control point of view is signal speed, signal stability and cost of the device**

A narrow bandpass filter (NBF) and photomultiplier tube (PMT):

- Very high speed as signal converted to a voltage output within a millisecond, no drift or temperature effects, moderate cost, but only 1 gas or metal monitored

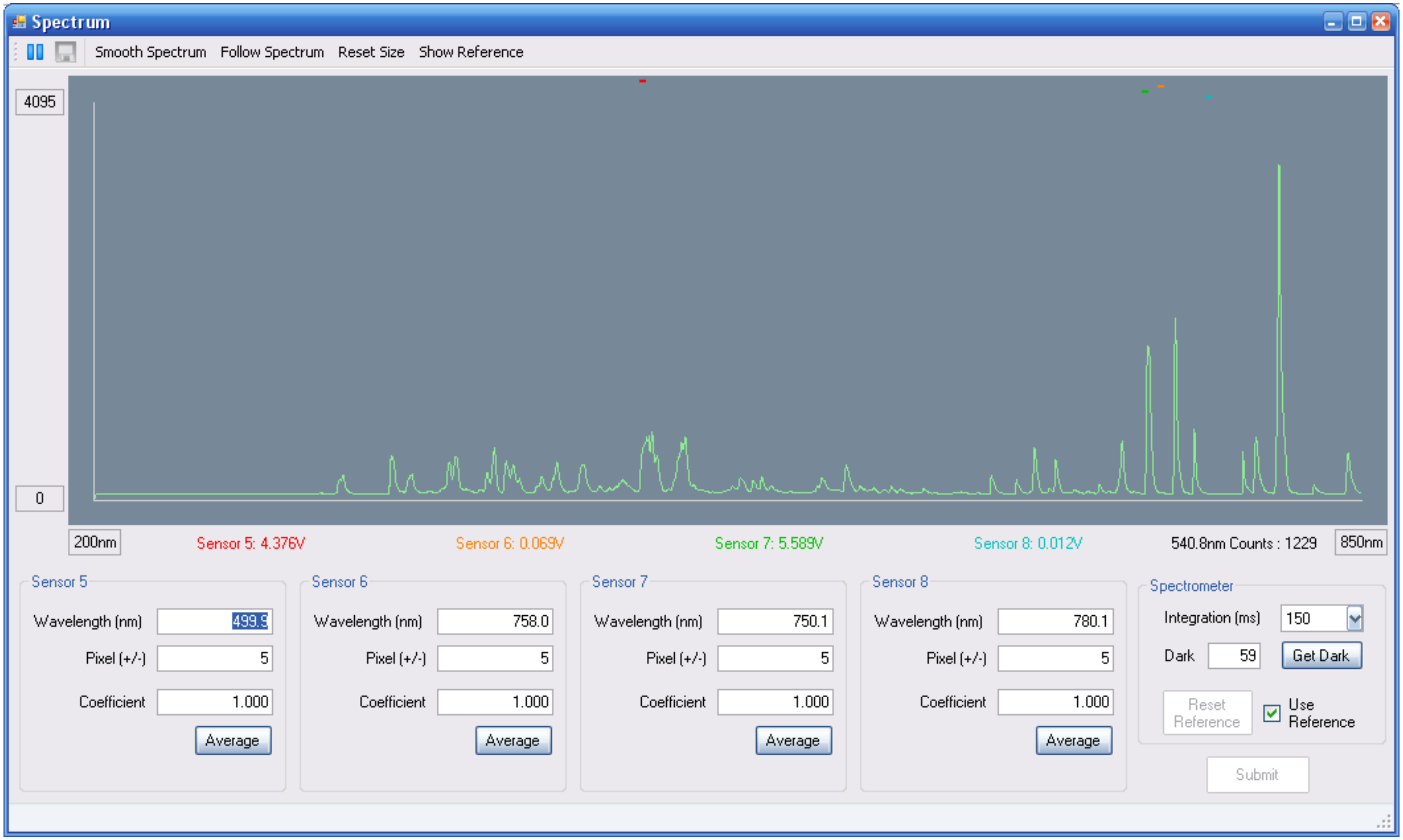
An optical spectrometer:

- Lower speed as typically integration time is in the 100's of milliseconds to ensure a good signal to noise ratio, subject to 'drift' as based upon CCD arrays (auto recalibration required), higher cost depending upon the resolution and sensitivity, can combine multiple species and ratios

Spectrometers freedom to choose any wavelength

Different wavelength channels can be combined to control around gas ratio’s

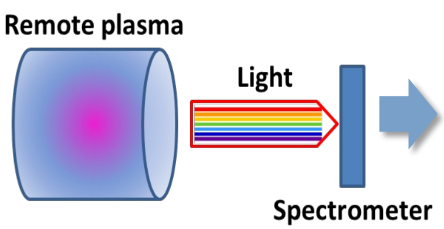
Useful for R&D as more flexibility especially if In and Ex P.E.M Situ combined

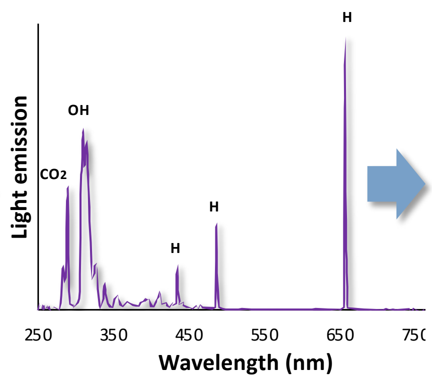


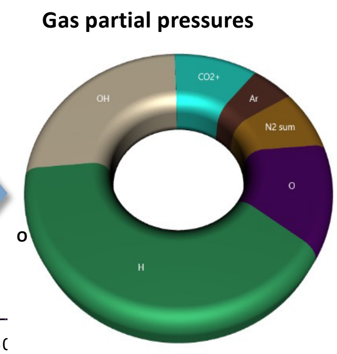
# ‘Remote’ light emission based sensors

Remote sensing of gas species provides a more stable signal – <u>light fluctuations  from the process plasma due to substrate movement or arcs not seen in the remote signal – unbeatable signal stability</u>


- Only the excess gaseous species monitored and can be combined with either a PMT or Spectrometer (OPTIX)

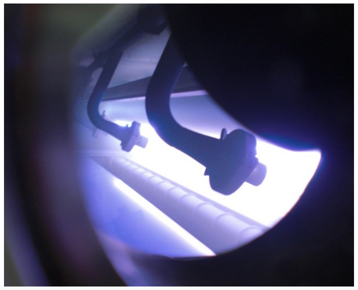


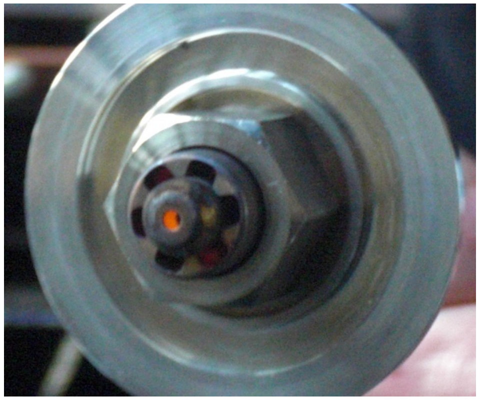



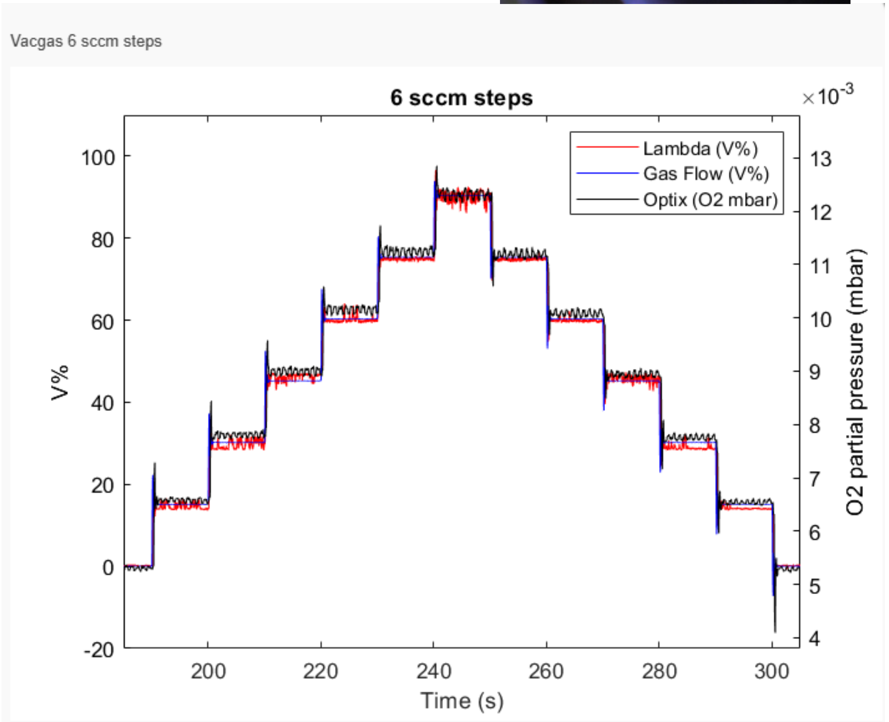

# Remote or in-situ Oxygen Sensor

Lambda based sensor provides an $O_2$ partial pressure



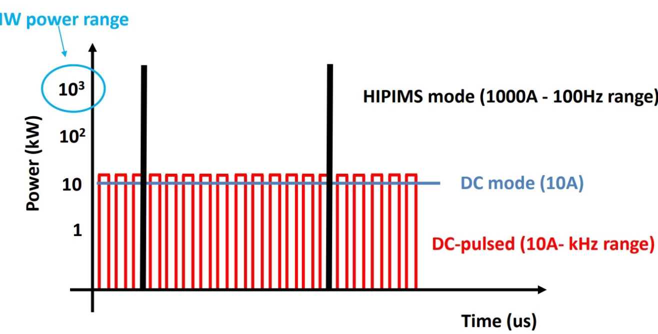
- High stability as VacGasG16 controls the sensor head temperature precisely and not subject to plasma fluctuations
- Similar cost to PMT
- Similar response as spectrometer

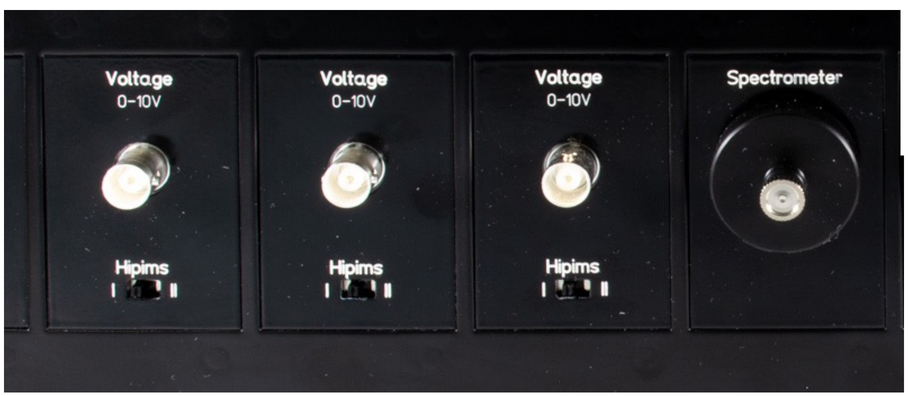


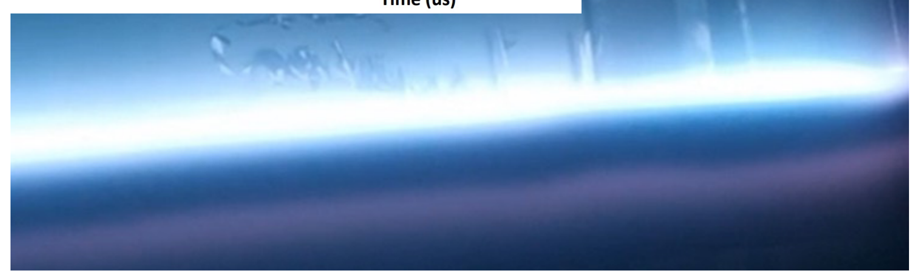
# What about Hipims

## Hipims – High Power Impulse Magnetron Sputtering Shows Hysteresis

- Hipims has a period pulse hence 'fast' sensors such as target voltage and PMT require signal capture – Hipims 'switch' is extra hardware that provides a constant signal from the pulse
- Slower sensors such as a spectrometer or VacGas G16 (Lambda) work as normal



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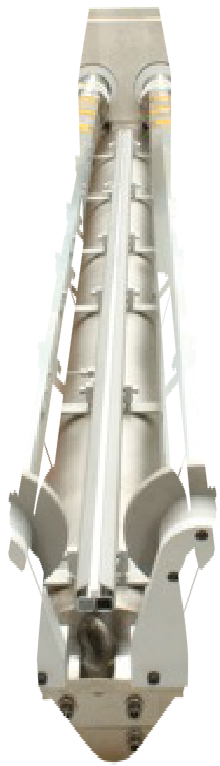
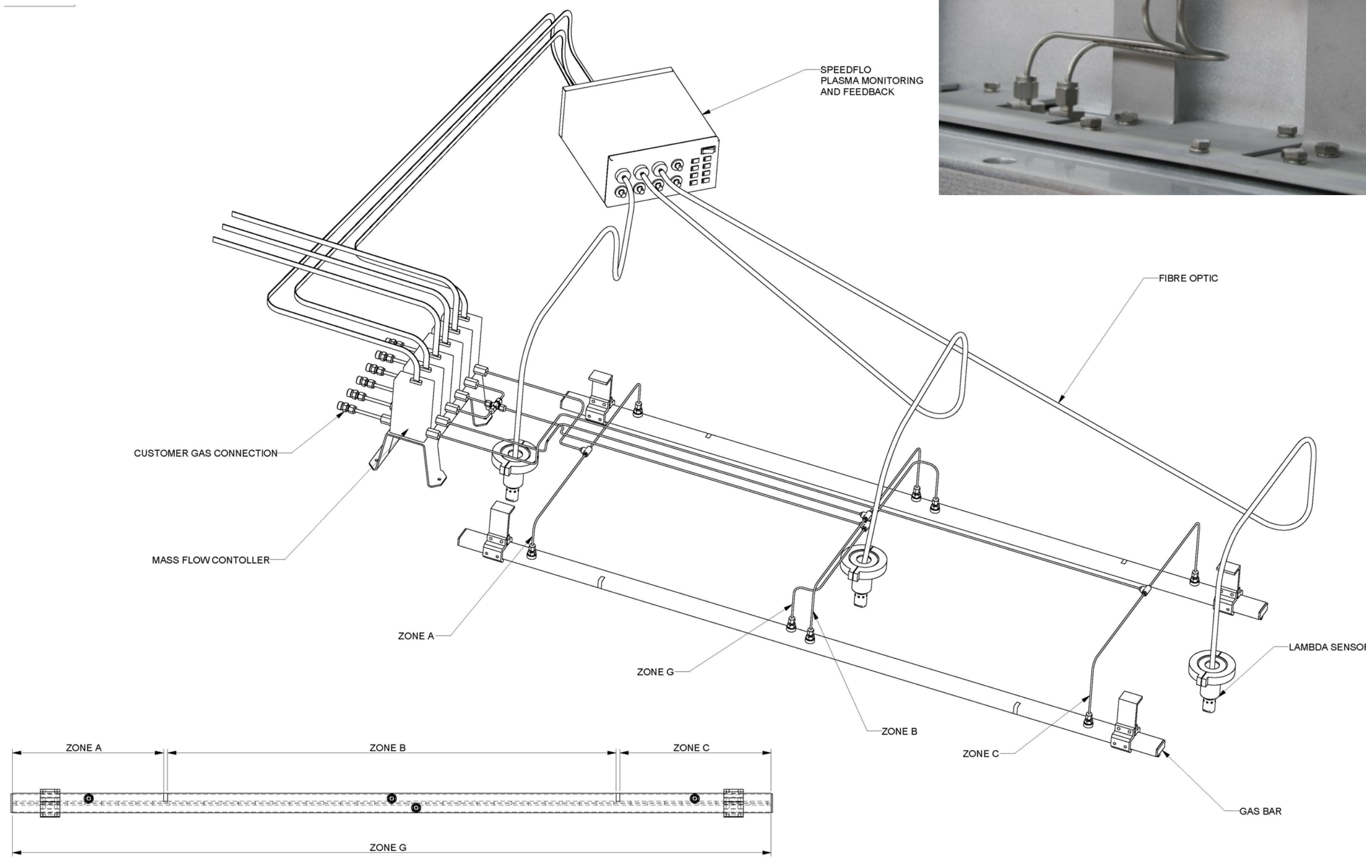
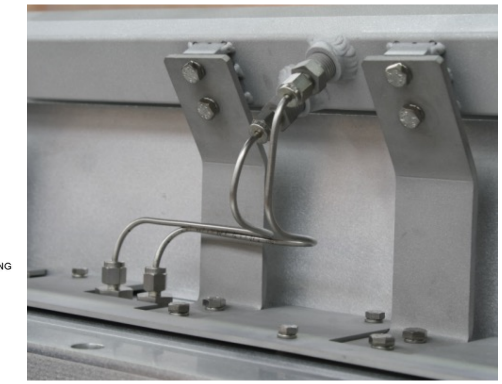
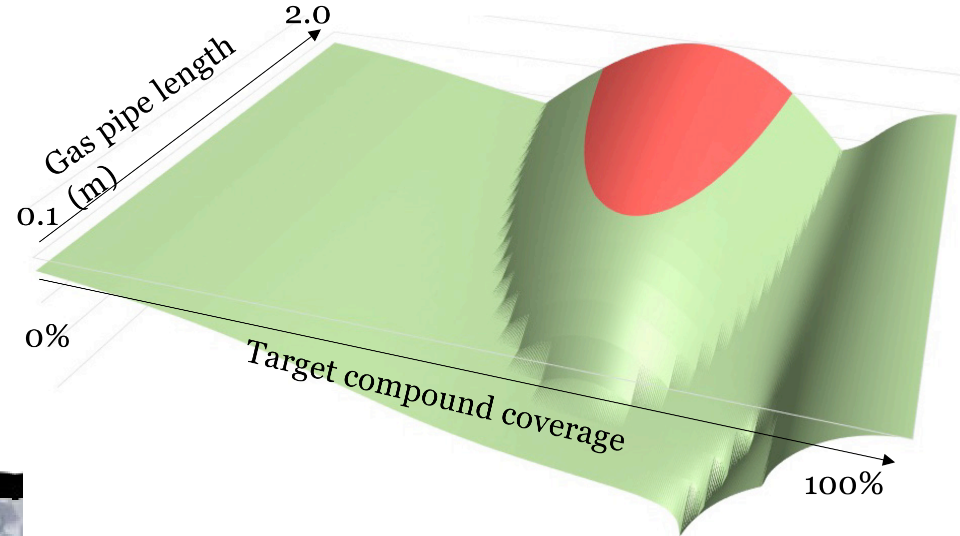
# Optimum gas bar designs and sensor locations as well as the length of gas connections and MFC response times all have an influence on the closed loop control



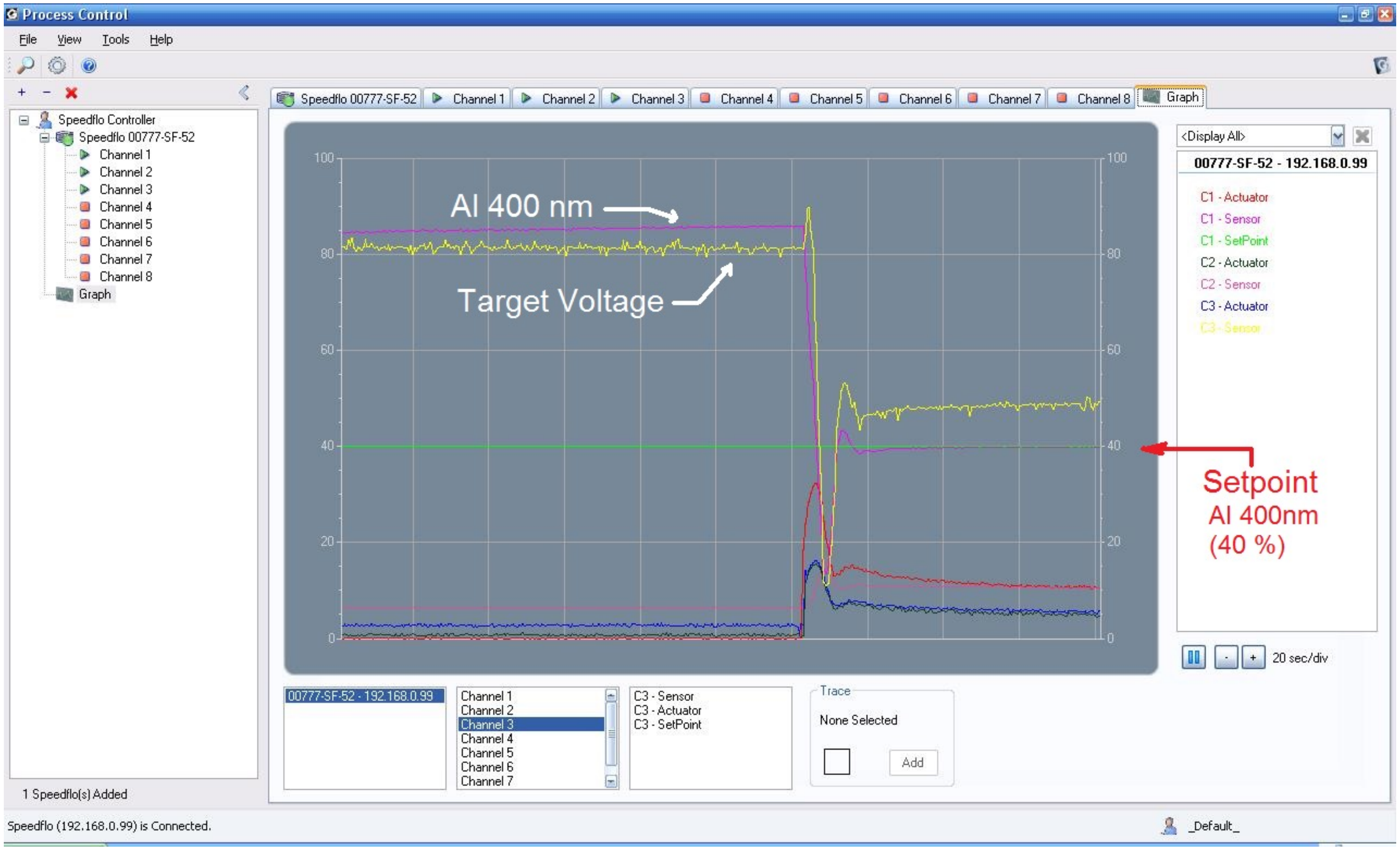


Fast responding target material systems may not allow control across all settings if for instance the gas flow through the delivery tubes has a delay – ie long gas pipe lengths

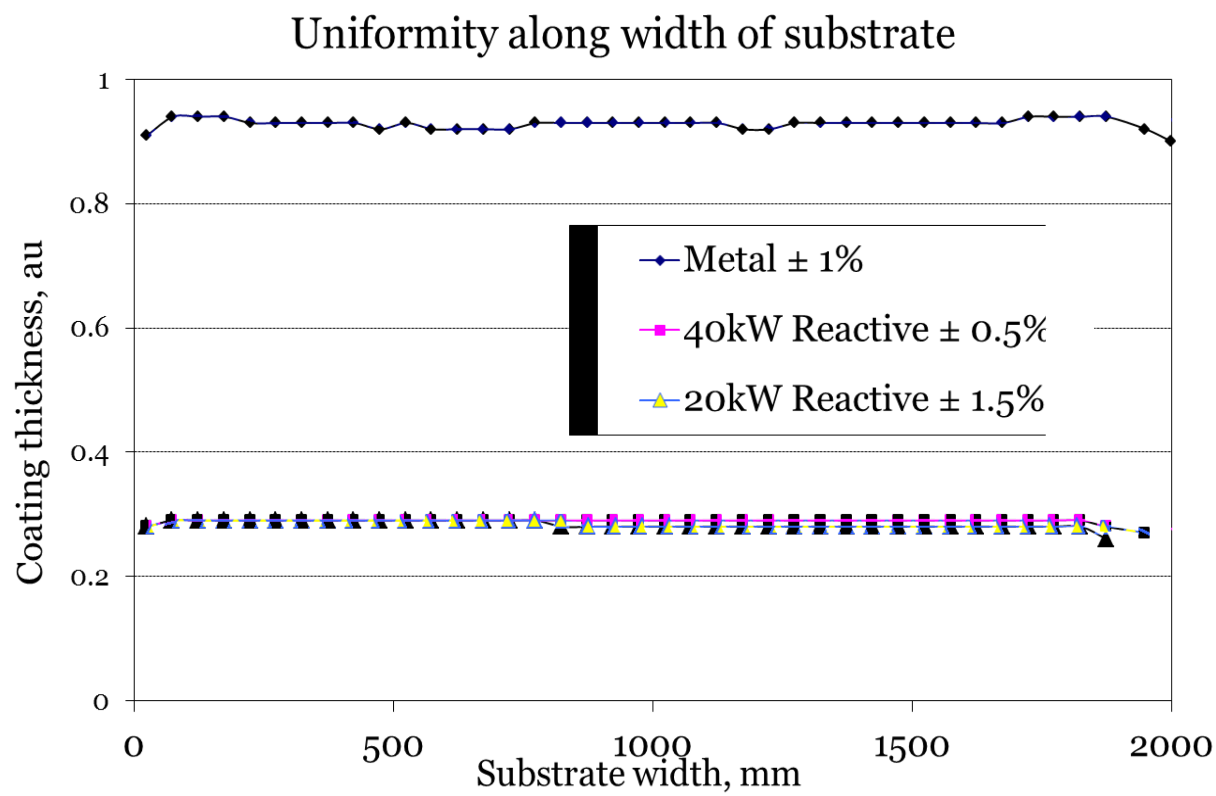



# Example of reactive gas control for $Al_2O_3$ on web for ultra-barrier applications



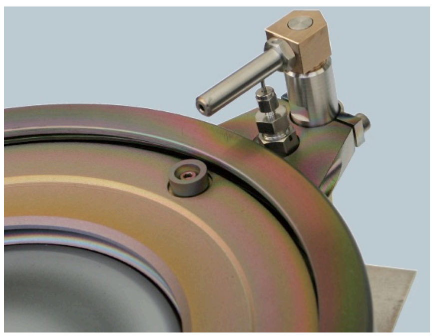
# Muilti-zone reactive sputtering has the ability to improve coating uniformity by local feedback control loops

- By having ability to sense and control different gas zones across a large area plasma gives the ability to get tight control of uniformity
- The flexibility of the controller software as well as gas bar design is the key to success



# Summary of available sensors

## In-situ



## In/Ex-situ


## Ex-situ

# Choosing between Speedflo Controller Types

Three different units are available based upon the number and types of input / outputs required

| *SPF/M Mini Speedflo* | *SPF16 Speedflo* | *SPF Speedflo* |
|---|---|---|
| **2 input Channels with 3 MFC outputs** | **Upto 16 Channels with mixed configuration between input or output, 'plug and play'** | **8 input Channels with 8 MFC outputs** |
| **1-2 voltage input (target voltage, VACG16, OPTIX analogue)<br>1 plasma emission input (in/ex situ, spectrometer or PMT)** | **1-16 voltage input (target voltage, VACG16, PMT, OPTIX partial pressure)<br>Output number is 16 – minus input number** | **1-8 voltage input (target voltage, VACG16, OPTIX analogue)<br>1-4 plasma emission input (in/ex situ, 1 spectrometer max or 1-4PMT)** |

# SPF/M Speedflo Mini

## Cost effective fast reactive gas feedback controller for smaller scale systems requiring fewer input / outputs.


- ***All Speedflo models have the patented auto-tuner***

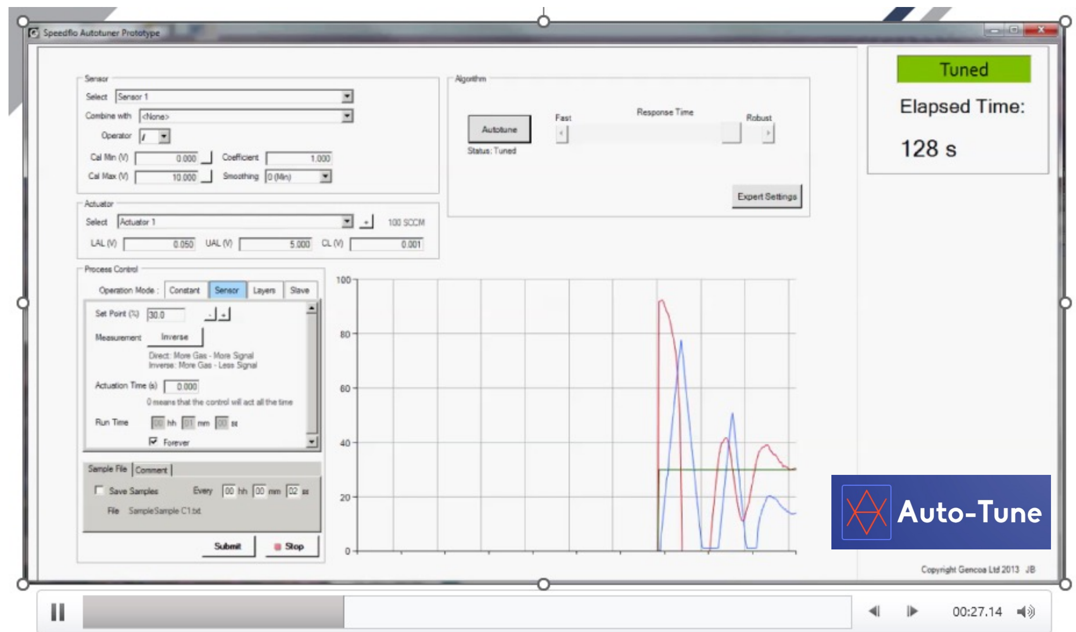
*SPF/M Mini Speedflo*

**2 input Channels with 3 MFC outputs**

**Input channel can be mixed between 1-2 voltage input (target voltage, VACGas G16, OPTIX analogue)**

**& 1 plasma emission input (in/ex situ, spectrometer or PMT)**

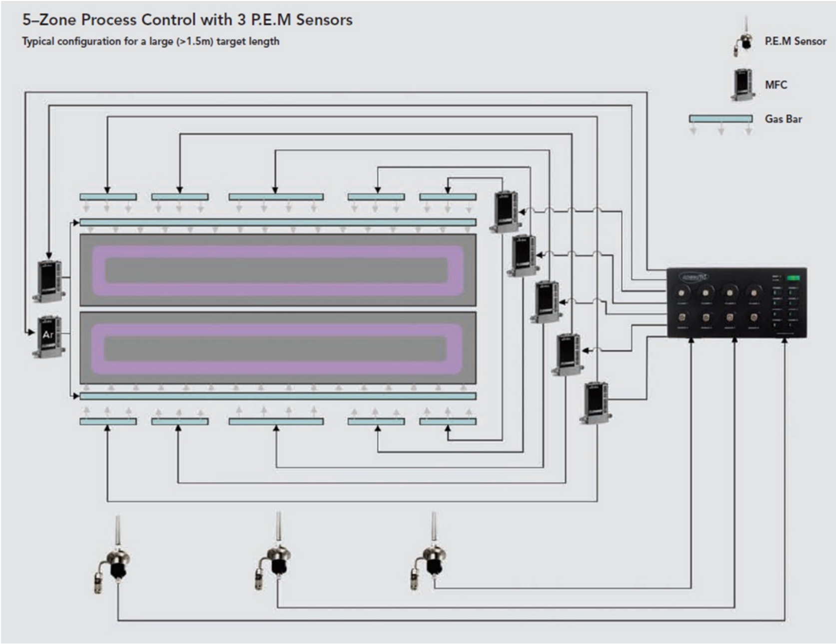
**Optional 2 channel Hipims 'switch' input**



# SPF Speedflo

**Industrial fast & configurable reactive gas feedback controller for large scale systems requiring multiple input / outputs.**


- *Workhorse for large area process control requiring zone control*

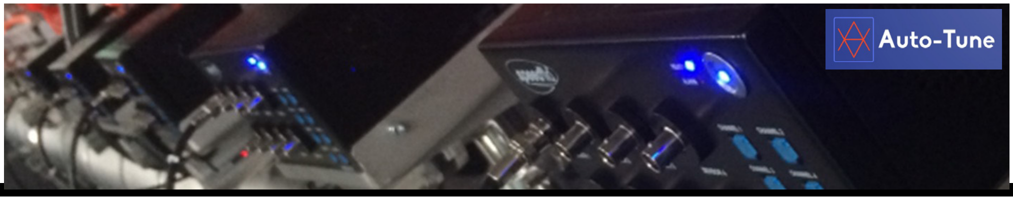



*SPF Speedflo*

**8 input Channels with 8 MFC outputs**

**Input channels can be mixed between 1-8 voltage input (target voltage, VACGas G16, OPTIX analogue)**

**& 1-4 plasma emission input (in/ex situ, spectrometer (1 only) or PMT (upto 4)**



# SPF16 Speedflo

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**Flexible reactive gas feedback controller any possible control situation which can be easily reconfigured**

- *Internal Controller Area Network (CAN bus) system to handle large amounts of data at high speed for millisecond control over upto 16 channels*

*SPF16 Speedflo*

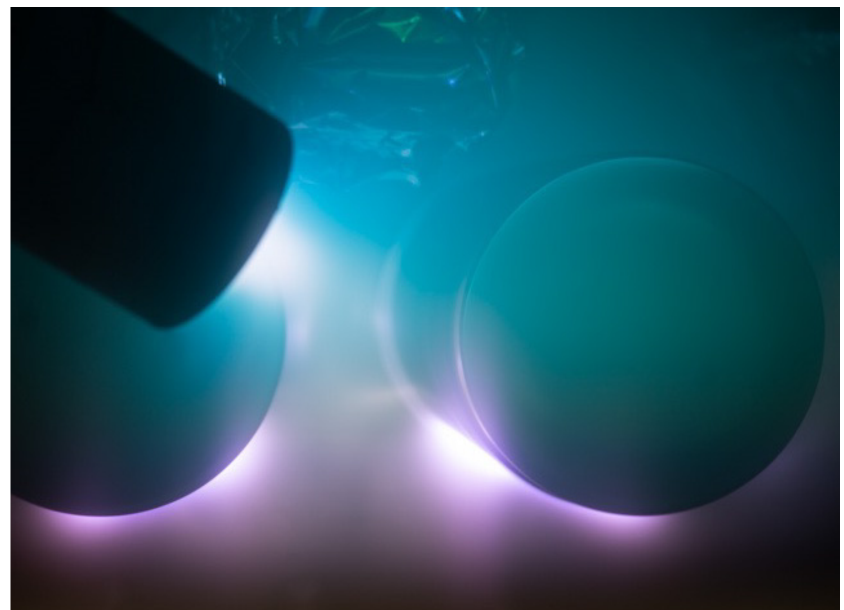
Auto-Tune

**16 input / output Channels can be configured in any way**

**Input channels can be mixed between voltage input (target voltage, VACGas G16, OPTIX analogue), plasma emission input (in/ex situ), spectrometer (upto 16) or PMT, hipims**

**OPTIX gas sensing input channel up to 16 with transfer of gas partial pressures (multiple gas or ratios)**

**Add or remove cards to change the configuration – Plug and Play at the process site.**



# Conclusions

- A wide range of sensors are available that ensures a suitable match for any reactive sputtering situation
- Depending upon the process scale, one of 3 controllers will ensure a good cost to complexity ratio
- Reactive sputtering feedback control can even the most complex problems
- Advantages of control are higher rates, better quality and improved energy efficiency