Microplasma Optical Emission Sensors for Process Chemistry Analysis

presented to the

American Vacuum Society – Northern California Chapter Plasma Etch Users Group

Chris Doughty
Verionix, Incorporated

Overview

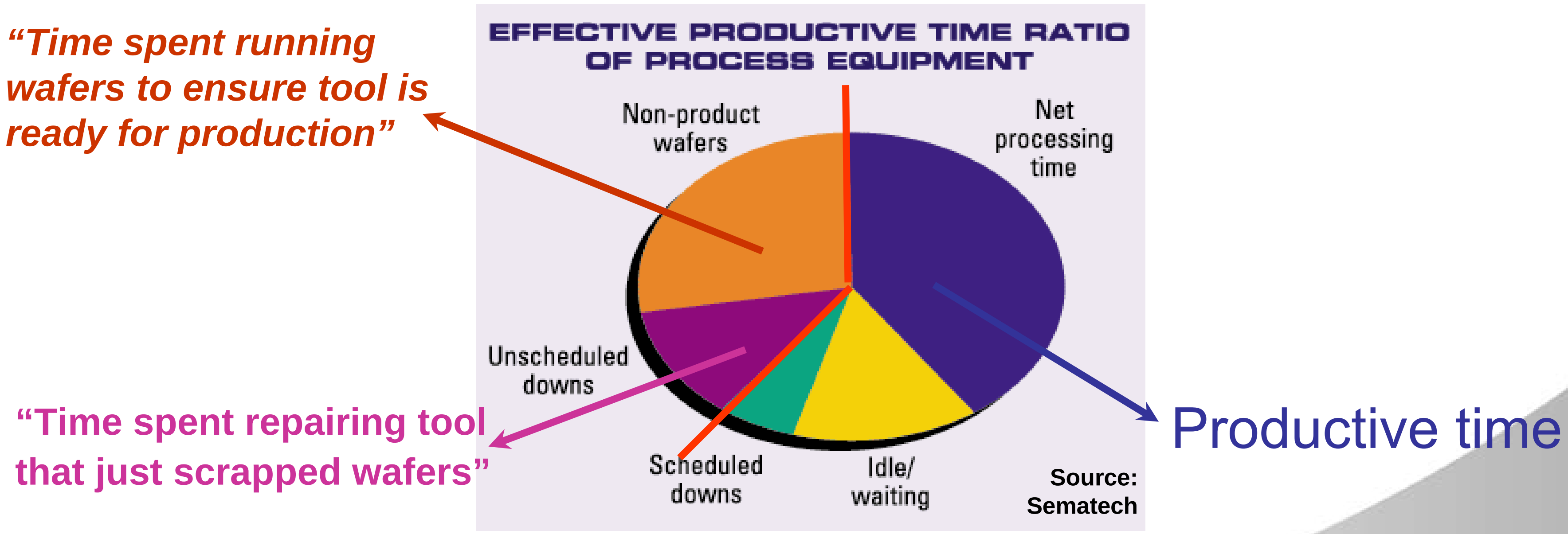
- Company Overview
- World View
- Sensor Technology and Operation
- Sensor Performance
- Application Examples
- Summary

About Verionix

- Technology
  - Founded in 2003 with exclusive microplasma technology
  - Compelling size, performance, and process compatibility advantages
  - Products share common core engineering, controls and outputs
- People
  - More than 70 years semiconductor industry experience
  - ASTeX, MKS, CTI-Cryogenics, Tokyo Electron, Intel, Bell Labs
  - Advanced degrees from UMd, MIT, UNC, Michigan, Northeastern
  - Expanding sales and support presence in United States and Asia
- Products
  - Gas chemistry sensors for process pressure to supply pressure (mTorr to atmospheric pressure).

World View

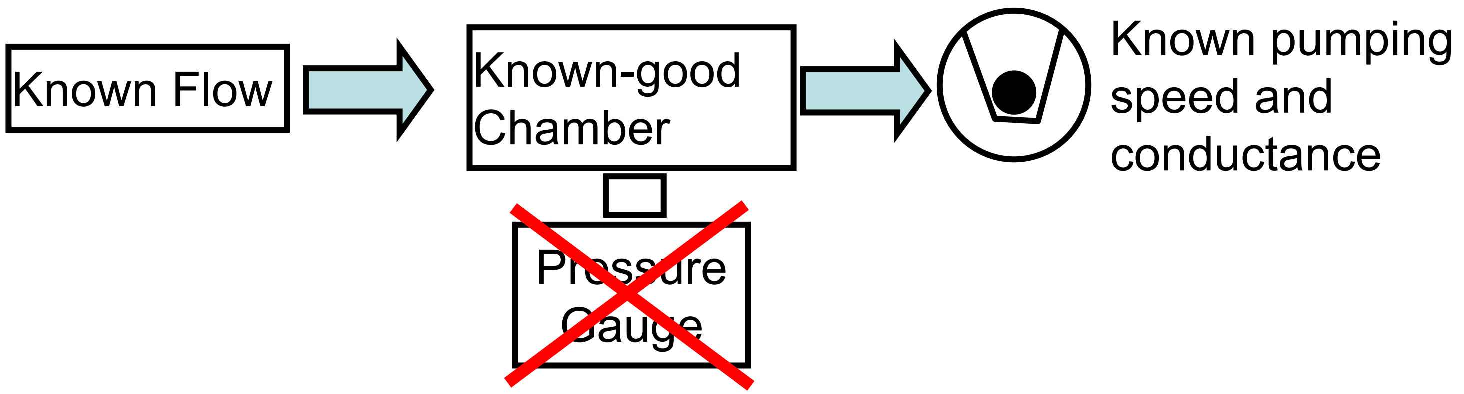
- Semiconductor Industry is Maturing
  - Lithography and wafer size improvements facing either technical or economic limits
- Productivity remains low measured relative to other fully mature industries
- Impact of downtime (via scrap) and non-product wafers are major opportunities to enhance productivity



Control Requires Measurement

- Critical Process Inputs
  - Temperature: Well-controlled at wafer chuck, chamber walls.
  - Power Inputs: Well-controlled at chuck (e.g. rf diagnostics).
  - Total Pressure: Well controlled
  - Process Chemistry:
    - Gas Purity, ID: last checked at bulk gas facility, bottle fill
    - Mixing: Trusting MFC calibrations, drifts
    - Chamber condition: procedures, pressure rate-of-rise tests?

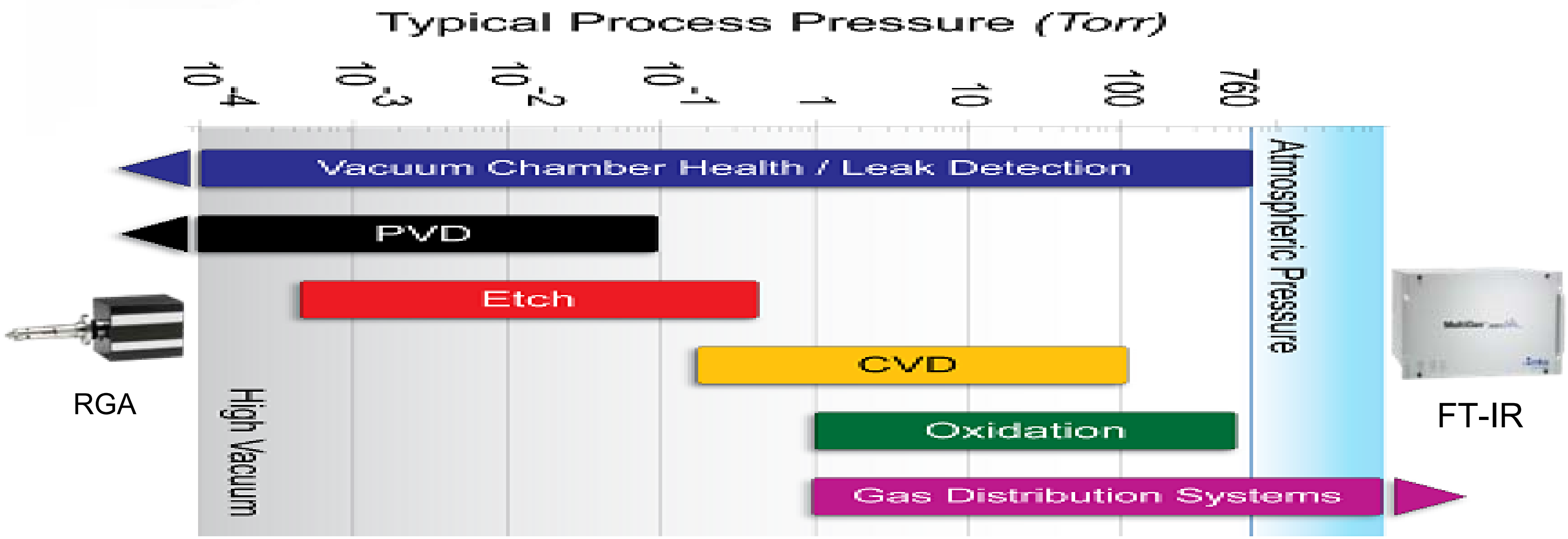
An Analogy



- No “theoretical” need for pressure gauges, BUT no one would consider building or operating a vacuum system without one.
- Today we typically operate blind in terms of actual process chemistry

Verionix

Process Engineering Needs



Process Tool ⟷ **Process-compatible Gas Analyzers**

Supply/Delivery Infrastructure ⟷ **Simple Point-of-Need Sensors**

Sensor Requirements

- Sensitive at required level
  - Goal is not ppt-level "analytical grade" instrument
- Simple and easy to use
  - Provide user (either human or system) with data of appropriate detail level (pass/fail match, critical SVID).
- Small
  - Must physically fit in crowded tool environment
  - Limited facilities requirements
- Robust, reasonable lifetime, easily serviced
  - Process compatible, no field calibrations required

Composition Sensors: Quad RGAs

- Ionization and charge-to-mass filters

- mfp > mass filter dimensions required ---
  - Low-pressure technology: Ideal for $P<10^{-4}$ Torr
  - Problems above 10^{-2} Torr without expensive, complex differential pumping

- Hot filaments incompatible with corrosives and aggressive gases

- Moderate complexity but widely understood spectral output

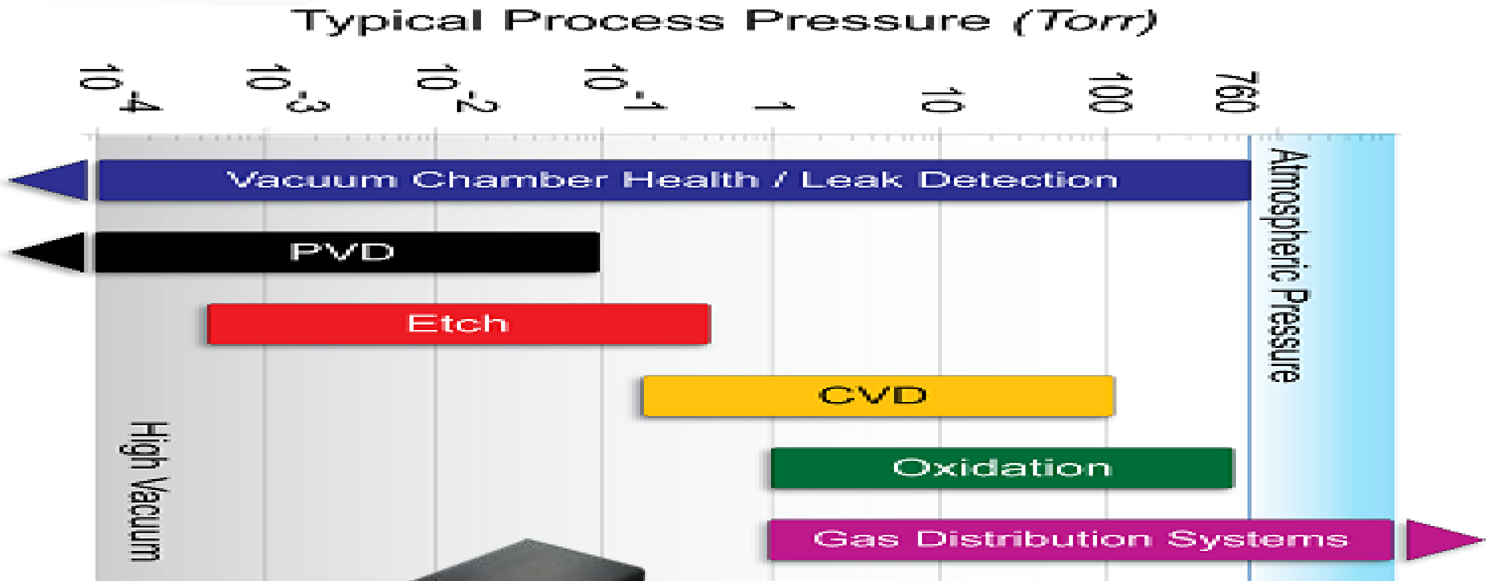
Absorption Spectroscopy (FTIR, NDIR)

- Beer's Law Signal ≈ Density,
  - Problems at low pressure (10^{-3} to 10^{-6} atm)
- Multipass optics- Extreme sensitivity to coating and attack,
  - Signal ~ R^n, n = 10s to 100s of reflections
  - R = 90%, 10 passes --- $(90\%)^{10} = 35\%$
- Spectral deconvolution is complex but tractable
- Diatomics, Inerts typically not IR active

Emission Spectroscopy for Vacuum

- History extends to 1970s
  - Varian SmartGauge
    - Penning or IG source + filter + PMT
    - N_2 detector, leak detector
  - Leybold OGC
    - Hot filament + filter + PMT
    - Primarily deposition controller
- Limitations
    - Hot filaments-limited process compatibility
    - Analog signal processing, bandpass filters and discrete detectors—interference problems and limited applications range without hardware reconfiguration
- “Information content” of spectral output remained untapped due to lack of small and cost-effective signal processing

Product Evolution



2005: Vx-2xxx Low-Pressure Process Gas Analyzers

2007: Vx-3xxx Atm-Pressure Process Gas Analyzers

2008 (Q4): Vx-6xxx Trace Binary Gas Analyzers

Verionix

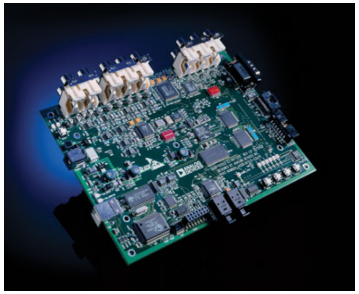
Sensor Technology

Sensor Technology

Light Emission → Light Detection → Signal Processing → Simple, Actionable, outputs

+

+



→

Compact, Low power, high intensity microplasma

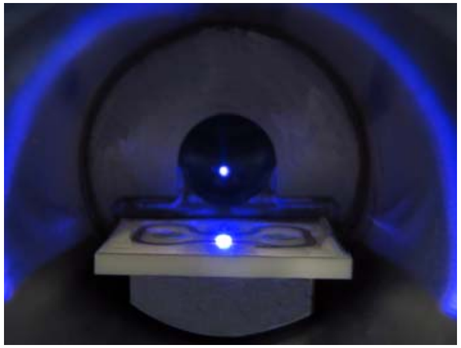
Miniaturized, array-based

UV-Vis-NIR Spectrometer

500 MHz DSP-based Controller and Real Time Data Reduction

Verionix

Microplasma Technology

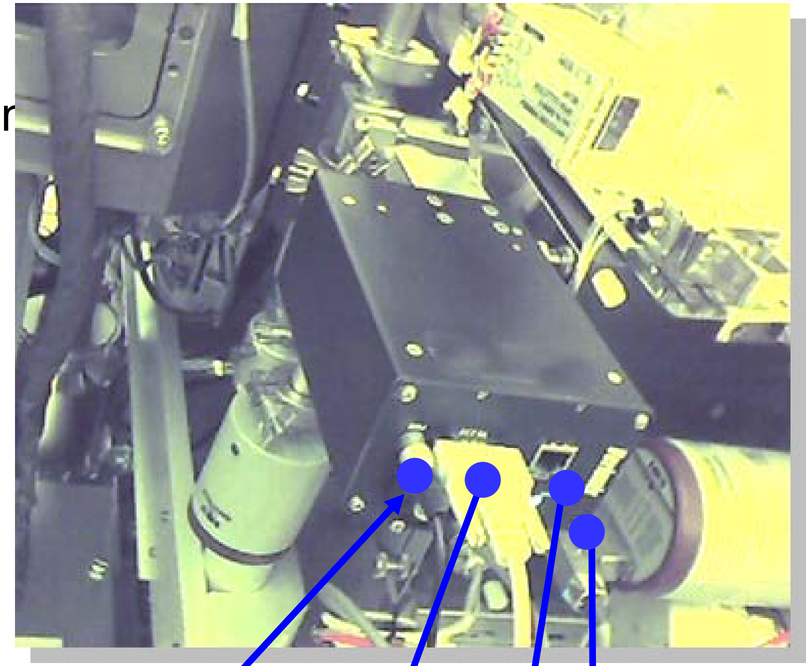


- High-power density, high-emission-intensity discharges
  - Inductively or resonantly coupled structures
  - 1 W/cm^3 ←→ MW/cm^3 power densities

- mm-length-scales
  - Reduce overall size→Enables small instruments
  - Reduce power requirements → use large market, high-reliability telecom components
  - MEMS/Microelectronics manufacturing technologies → Excellent repeatability and reproducibility

Direct process chemistry sensor

- **Direct-to-tool** Attachment
  - Standard NW25 Vacuum Connection
  - Small enough to fit "anywhere"
- Power and Data Connections
- **No** pumps
- **No** sampling orifices
- **No** cooling water
- **No** compressed dry air
- **No** PC required



24 V DC

RS-232 Data

Ethernet Data

Discrete A/D IO

Data to: Tool Controller,
FDC system,
Archiver/Logger
PC-based GUI

Multiple Application Points

Upstream of Process Chamber

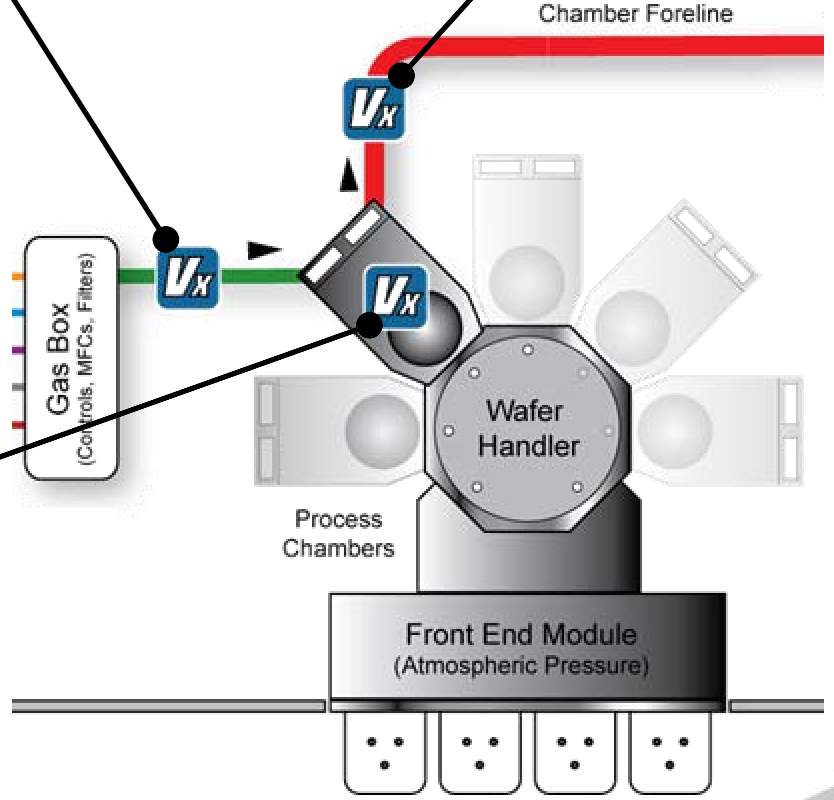
Gas Quality
Gas Mix Ratios
Gas ID

Downstream of Chamber

Effluents
Byproducts

Within Process Chamber

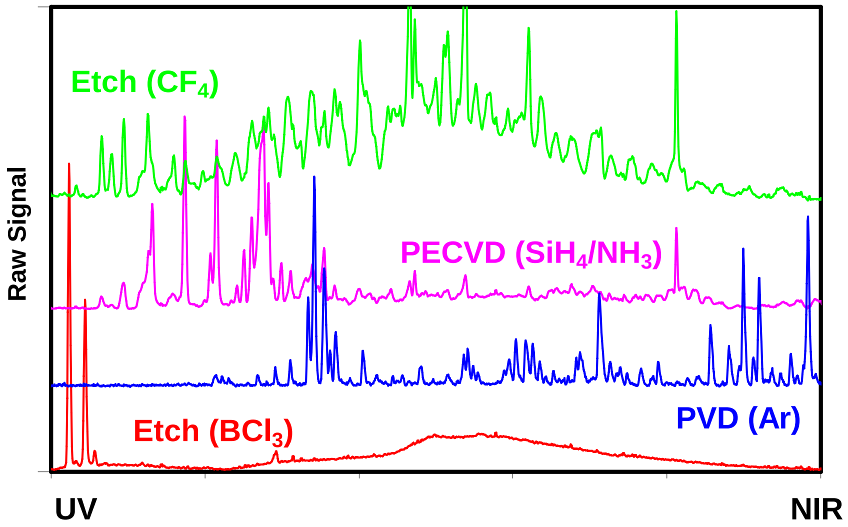
Incoming Gas
Process Byproduct
Chamber Condition



Sensor Performance

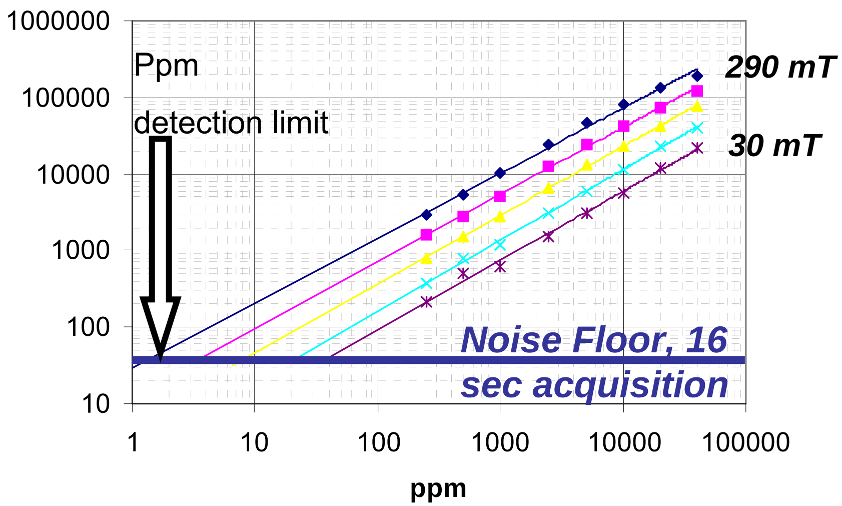
What can you See??

- In principle:
  - Anything that can be excited to emit in UV to NIR (200-850 nm) can be detected
  - Inerts, molecules, diatomic molecules, …
- Caveats
  - Weaker emitters harder to see (worse detection limits)
  - Overlapping signals

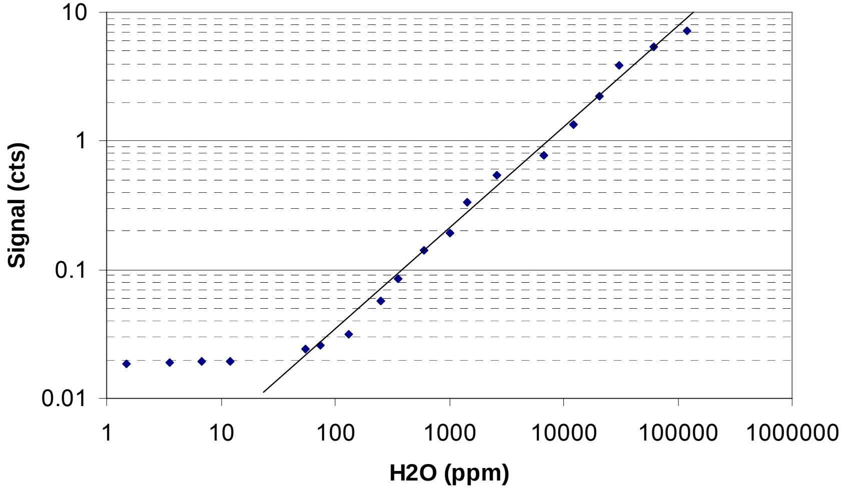


Vx-2300: Sensitivity to parts-per-million

Nitrogen in Argon

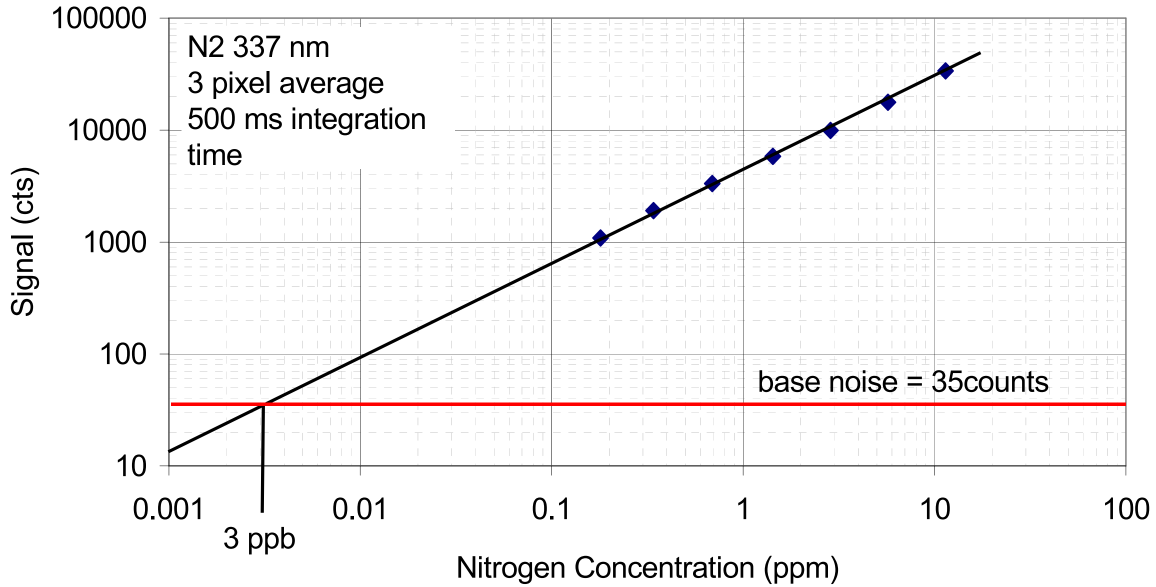


H2O in Argon



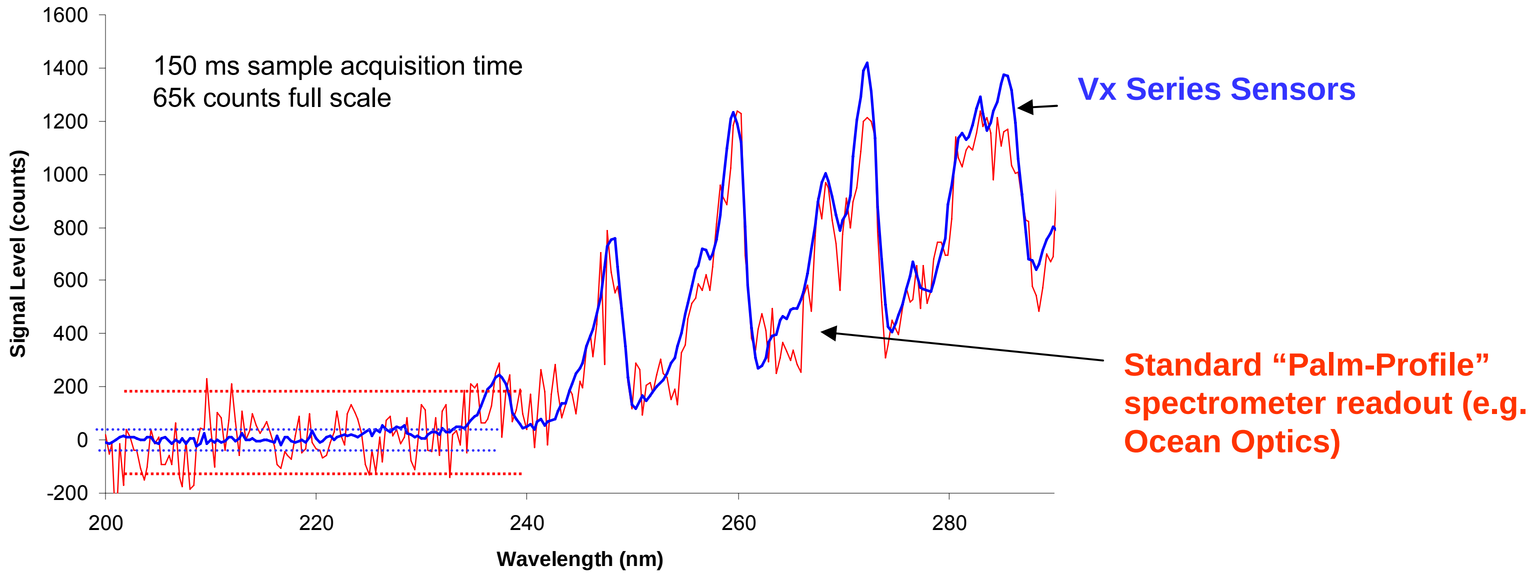
- Vx-2300 pressure range 10 mTorr to 1 Torr
- Detection Limit: SNR=1, Noise: 3-σ noise floor
- Single peak detection

Vx-3100 Sensitivity to parts-per billion



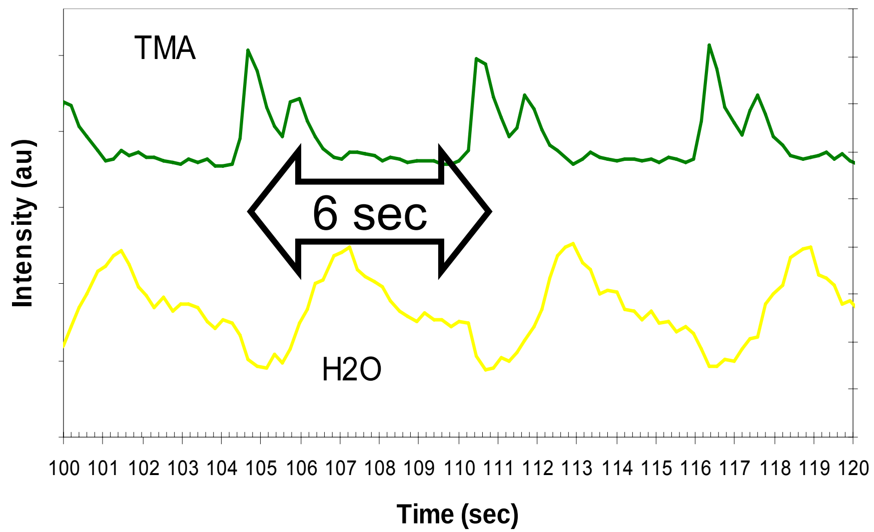
- Vx-3100 Pressure Range: 1 Torr to 2 atm.
- Detection Limit: SNR=1, Noise: 3-σ noise floor
- Single peak detection

High-Quality Signal Detection/Analysis



- Improved weak-signal Signal to Noise Ratio (SNR)
- Enhanced sensitivity at detection limit
- Dynamic Range = Maximum Signal / Minimum Detectable Signal
- Optical resolution 1.5 nm FWHM

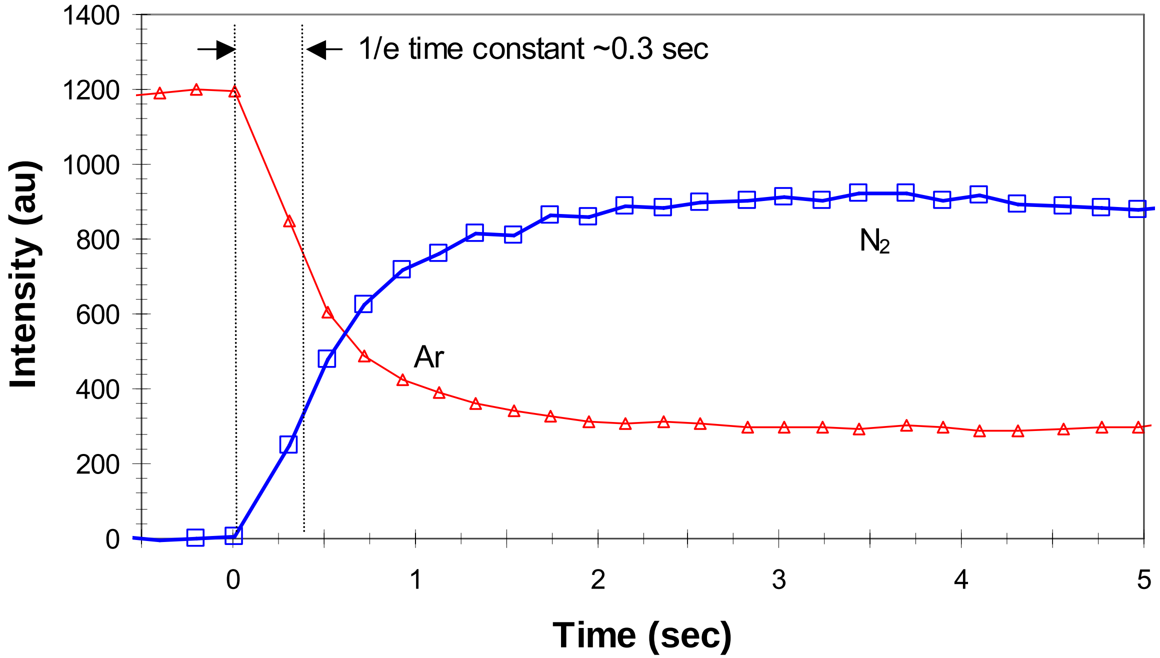
Sensor Electronic Time constant



- Data Acquisition and detection time
  - 100 ms to 5000 ms intrinsic detector “integration time” (i.e. shutter speed)
  - Firmware based averaging
- Data-Latency
  - Time delay, acquisition to output <0.5 secs

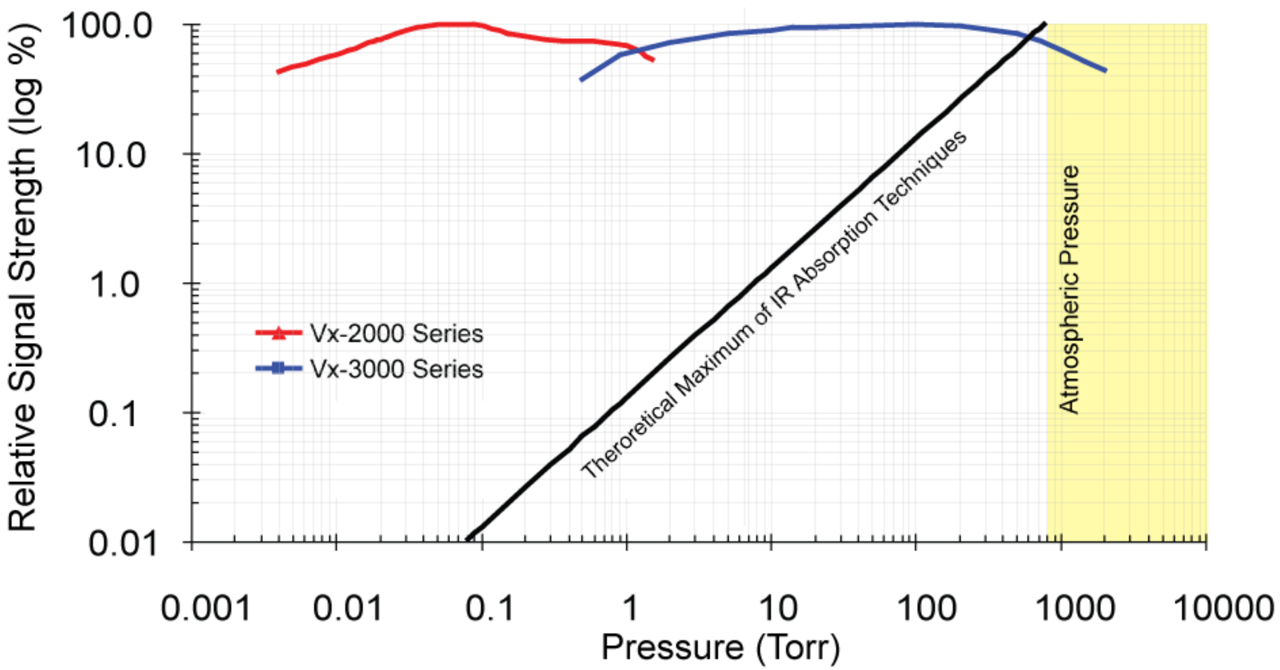
Verionix

Gas exchange time constant



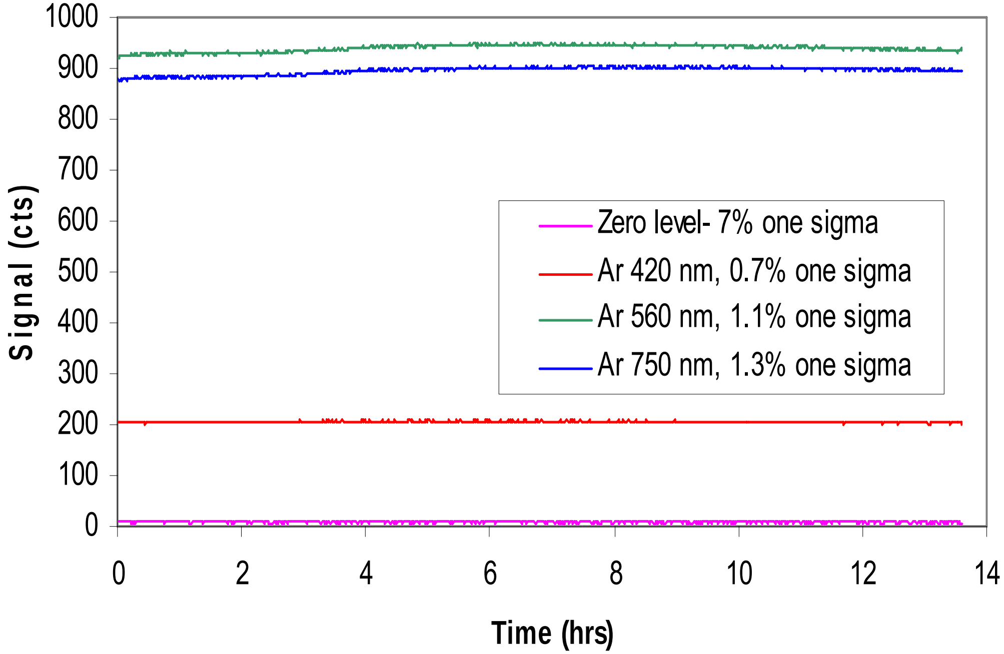
- Ar to N_2 gas change at t = 0, 200 mTorr, dead-leg" configuration-Relies on diffusion for transport within sensor
- Exchange time constant depends on flow velocity or diffusion time constant

Pressure Dependence



- Emission intensity depends on source efficiency vs. pressure
- Absorption techniques intrinsically linked to absolute pressure➔ need long path lengths and multipass optics as pressure decreases

Signal Stability

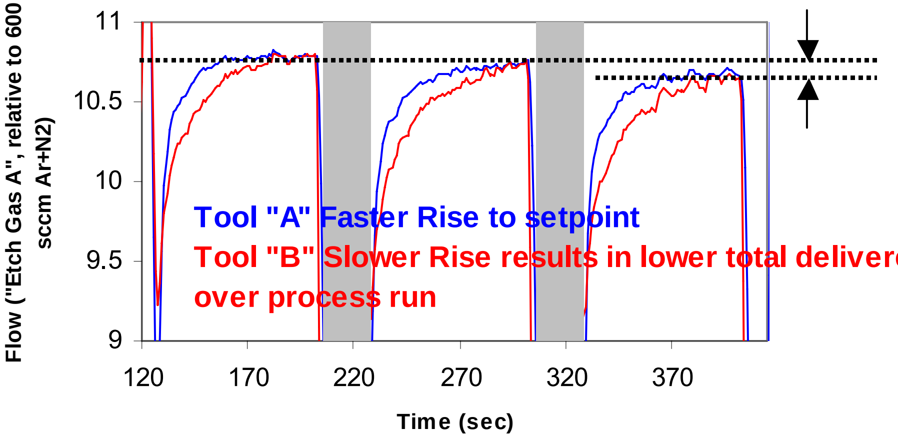


- 14 hr time base
- Open loop operation, Constant source operating parameters
- <1.5% signal stability (emission source, detector drifts + test stand drifts)

A Few Applications

Vacuum to ATM Gas Composition

Variations in Composition Delivered from a Gas Box



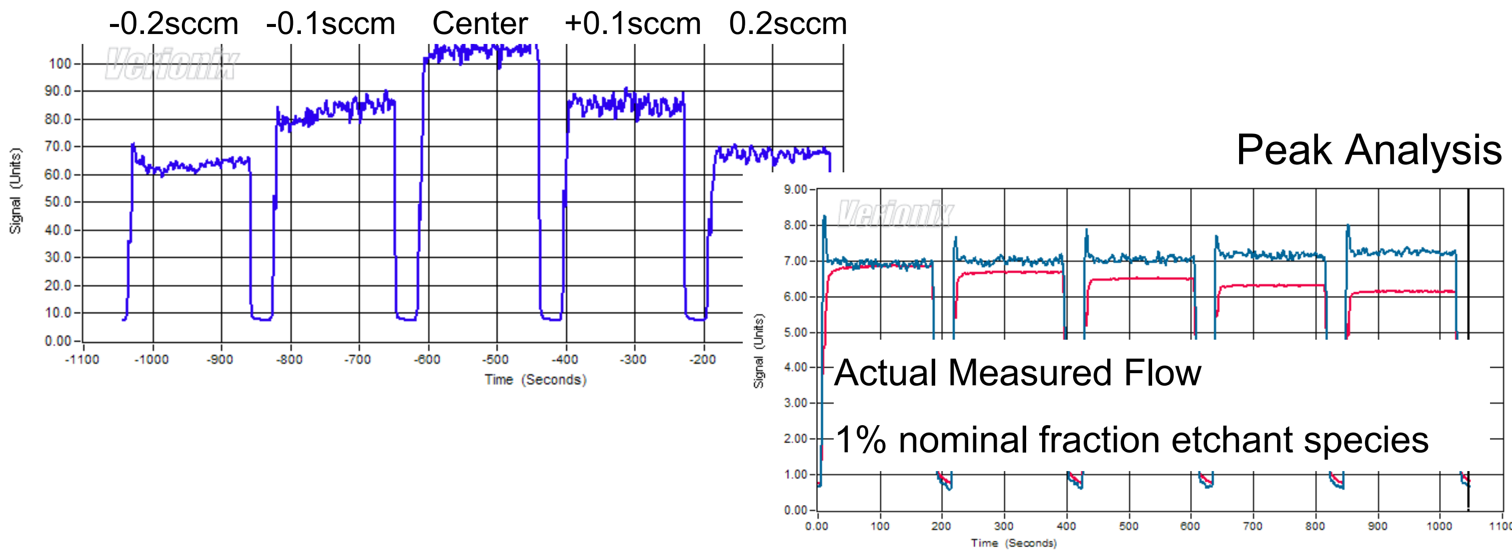
Residual 1.5% variation caused by incompletely equilibriated "First Wafer" effect

For this process, 0.1 sccm variations known by customer to impact process

- Problem:
  - Small delivered gas variations cause process variation, wafer-to-wafer, tool-to-tool.
  - Gas box "settings" and its "delivered" composition vary as result of gas box design, tool configuration and process operating sequence.
- Critical Verionix Data:
  - Sensor measures real-time concentration of both etchant and inert (diatomic/noble) gases.
- Result:
  - Chambers can now be matched to insure for better process consistency
  - Variations in process as result of component aging, failure and operating mode are detectable

Process Flow Validation

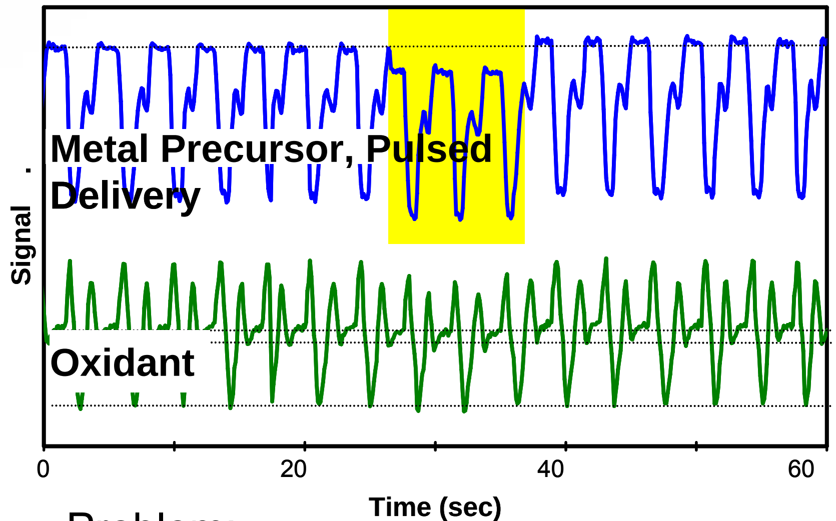
Fingerprint Analysis (whole spectra)

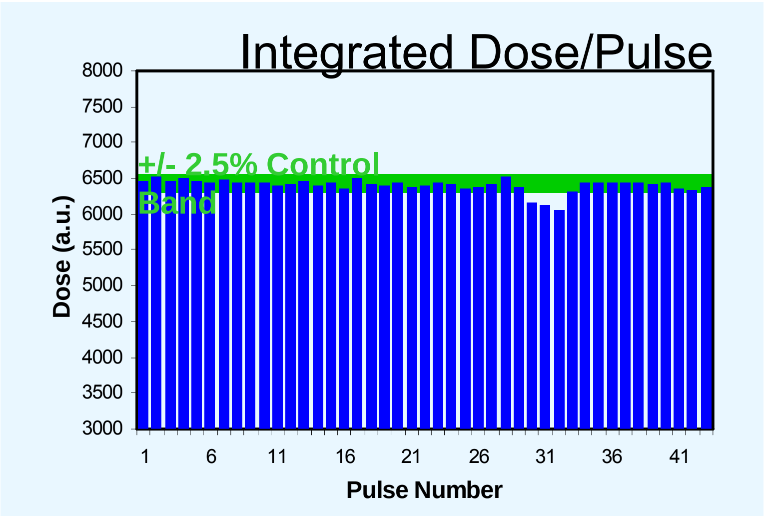


- Species: Freon in Argon:Oxygen:Freon mix (98:1:1) @ 250 mTorr, 1000 sccm flow
- Traces decreasing in 0.1 sccm increments
  - Trace gases varying simultaneously
- Method
  - Instantaneous composition monitored with multi-peak algorithm
  - Composition monitored at chamber input

Rapid-Response Detection of ALD Valve Faults

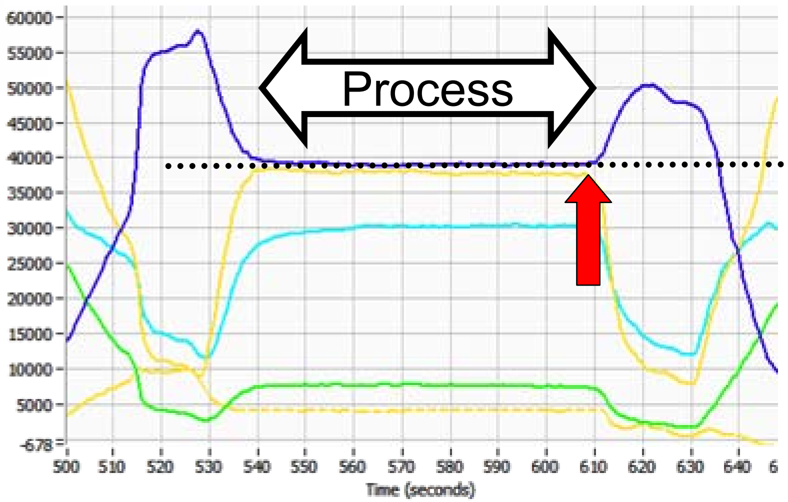
Instantaneous Composition Signal



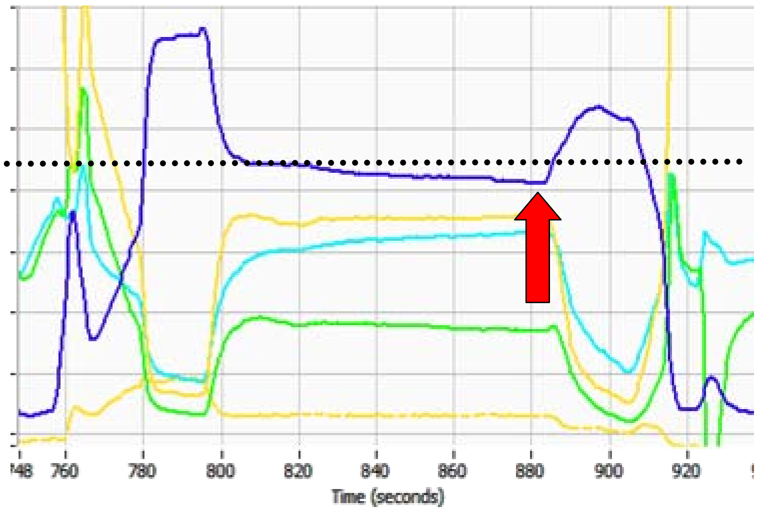


- Problem:
  - Valves used to pulse ALD precursor (TMA) are subject to degradation & random failure.
  - Rapid pulses require fraction of a second responsiveness to detect faults as they occur.
- Critical Verionix Data:
  - Sensor samples real-time concentration of both precursor and oxidant (water vapor) @ 10 Hz.
- Result:
  - Faults in ALD can be detected as they occur, reducing scrap and boosting tool productivity.
  - ALD valves can be monitored and replaced before failure, assuring continued productivity.

Vaporizer faults in Sub-Atmospheric CVD Chamber



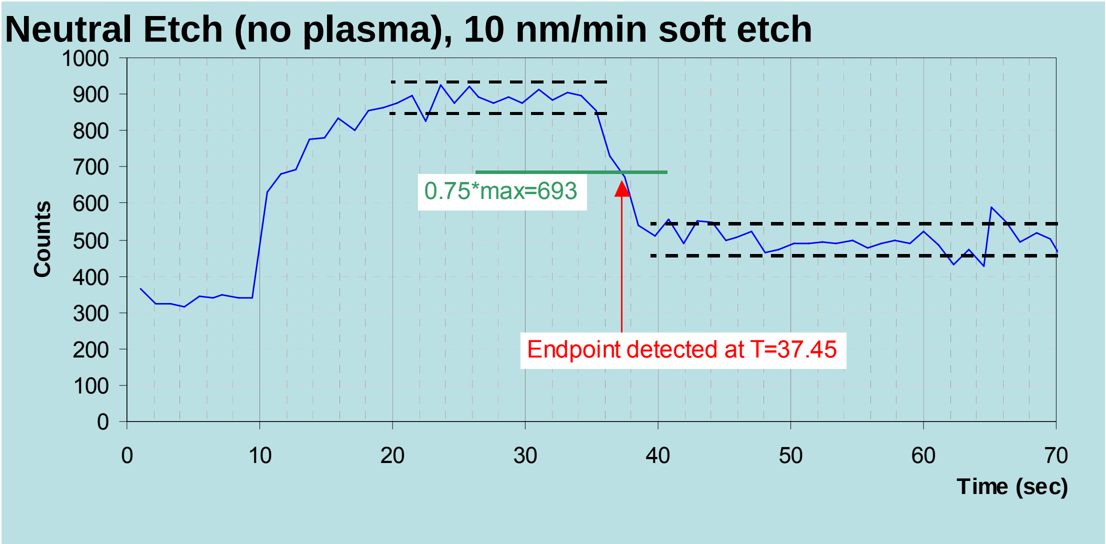
"Good" Chamber & Process

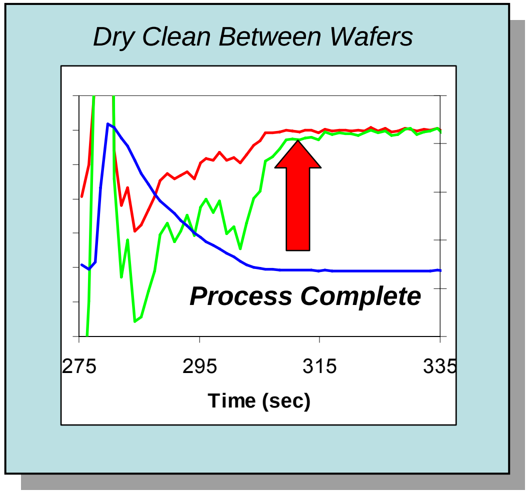


"Bad" Chamber & Process (Drifting Composition)

- Problem:
  - Clogging & instability in chamber's vaporizer causes film de-lamination & yield loss.
- Critical Verionix Data:
  - Allows variations in process performance from desired process signature to be identified
  - Notes instabilities in tool process chemistry over entire process cycle
- Result:
  - Malfunctioning chamber removed from service before wafer scrap occurred.
  - Repair validated before committing wafers to tool

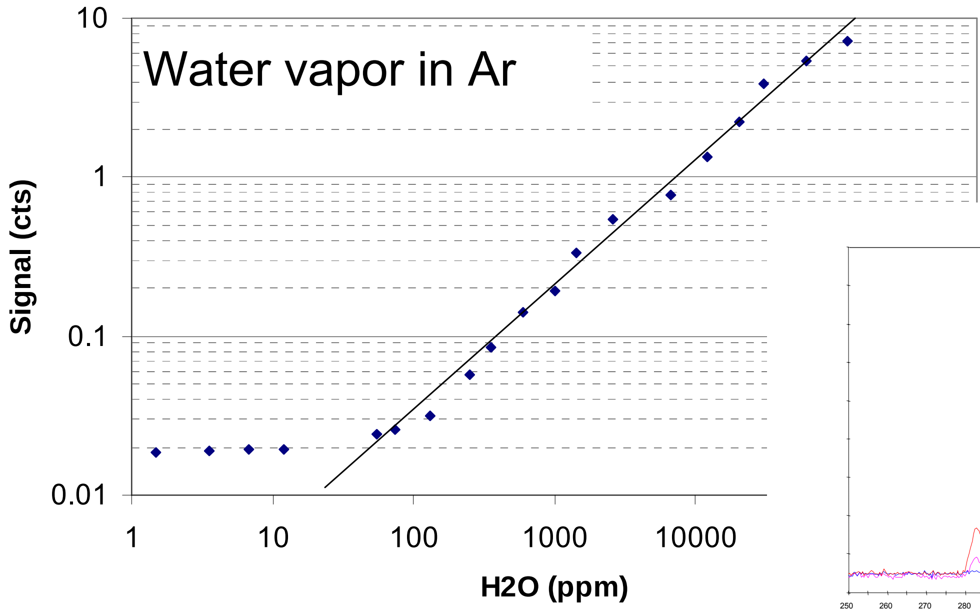
Endpoint Detection in Processes without Plasmas

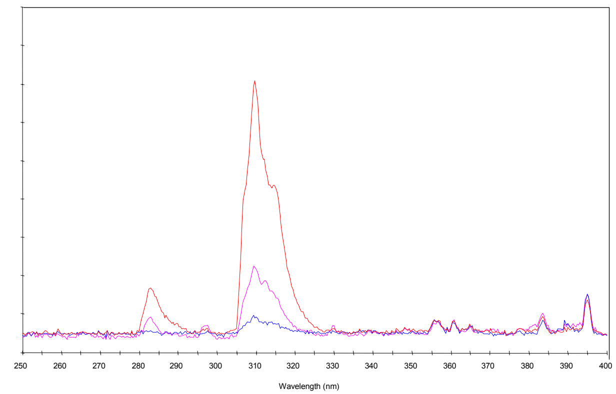




- Problem:
  - Convention OES endpoint detection ***requires*** process plasma.
  - "Downstream" processes generate no OES signal from process chamber
  - Result is processes running "open loop" with no feedback
- Critical Verionix Data:
  - Generate signal downstream of process chamber regardless of process type
- Result:
  - Process stopped at optimum time ensuring reduced device damage, increased tool lifetime and productivity

Moisture Detection

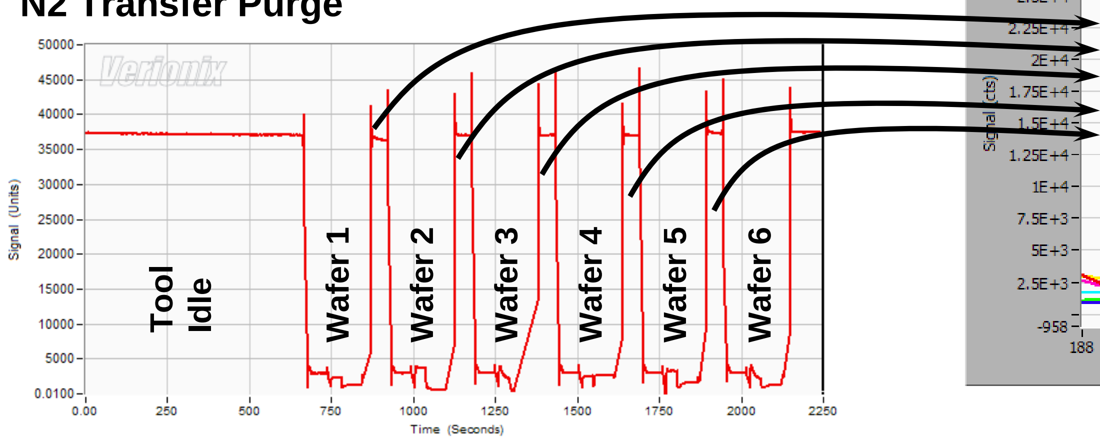




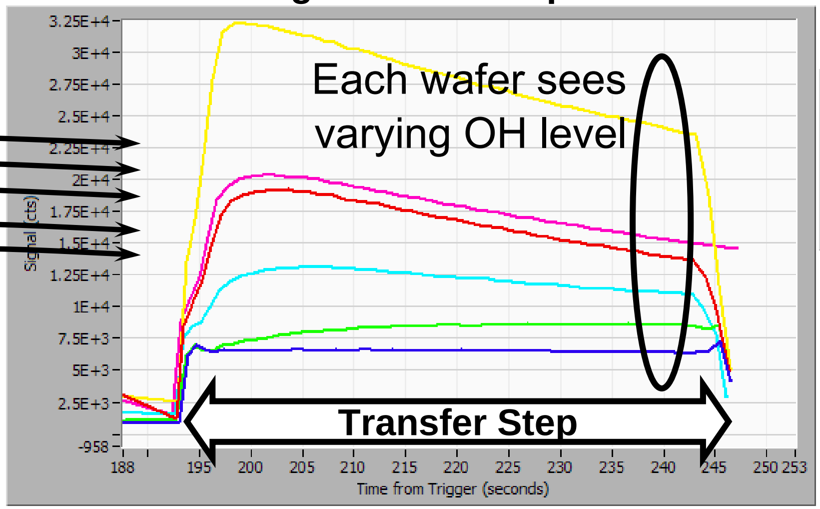
- System level moisture is sum of
  - Incoming gas impurity
  - Additional moisture pickup in facilities
  - Moisture on-tool from incomplete pumping, maintenance activities
  - Process reaction byproducts
  - Leaks

Chamber Recovery During Transfer Steps

N2 Transfer Purge

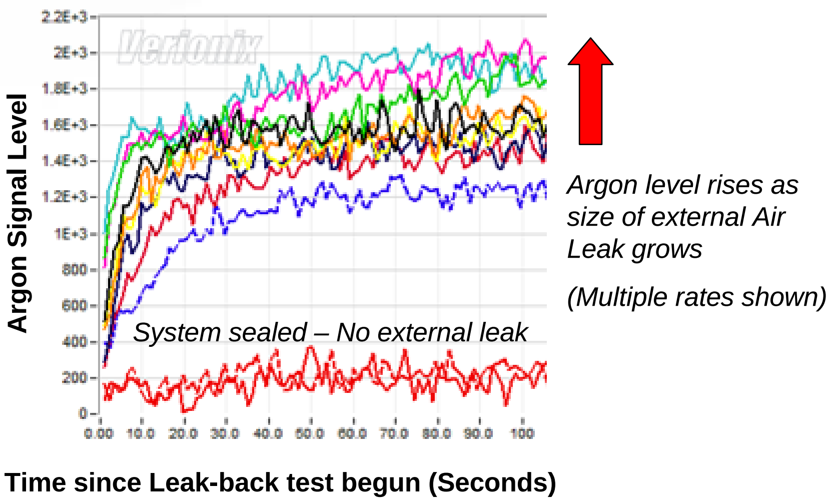


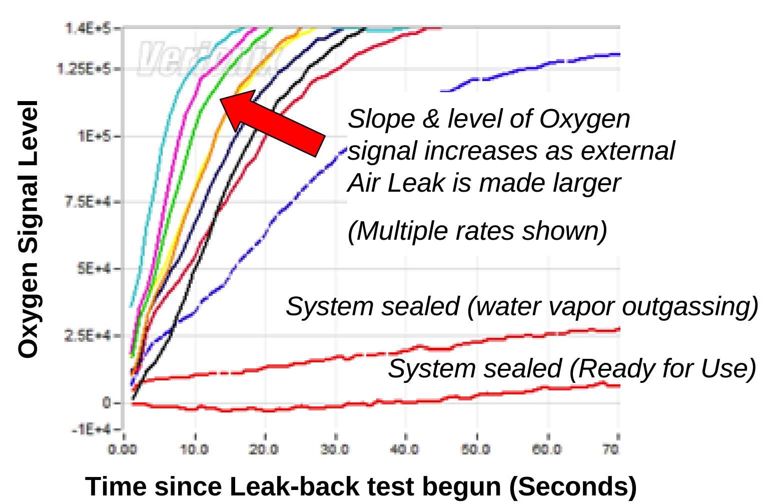
OH Levels during transfers steps



- Preceeding Wafer Process Step impacts following step due to incomplete recovery
- OH level impacts oxidation process results

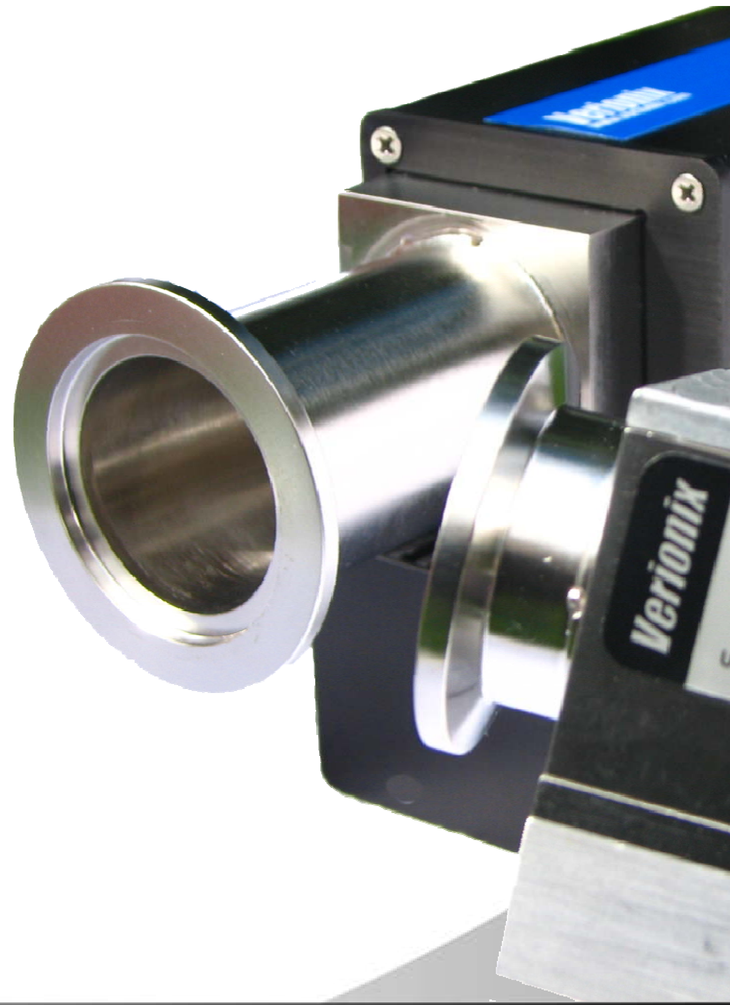
Detecting Vacuum System Failure in Real-time





- Problem:
  - Pressures reported during chamber "Leak-back" tests don't characterize leak sources (internal or external leak, outgassing, virtual leaks, water vapor, process residuals).
  - Identifying external leaks with He detectors is time-consuming, unsuitable for production use.
- Critical Verionix Data:
  - Changes in H, O, Argon, OH levels are monitored during "Leak-back" tests to < 20 mTorr
  - Argon level reflects rate of external leaks. H, O, OH show internal leaks & chamber condition
- Result:
  - "Leak-back" tests shortened. External leaks levels, Water vapor levels reported in "real-time"

Thank you



For more information, visit us at:

www.Verionix.com

Verionix