Infrared Spectroscopy for Process Diagnostics & Control

Technology for Productivity

ASTeX®
Baratron®
D.I.P.™
ENI®
HPS®
Mass-Flo®
On-Line™
PICO™
Spectra™
TeNTA™

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NSF/SRC Engineering Research Center for Environmentally Benign Semiconductor Manufacturing TeleSeminar

Outline

- IR Basics.
  - The whys and hows.
- Film Metrology
  - What's new in IR metrology.
  - The Films
    - Epi, Doped Oxides, MEMS, Photoresist and high-k films.
- Gas Composition Analysis
  - The Tools
    - Full-spectral and filter based instruments.
  - The Applications
    - Process Exhaust Investigation, Chamber Clean Endpoint, Scrubber Efficiency.
- Conclusions

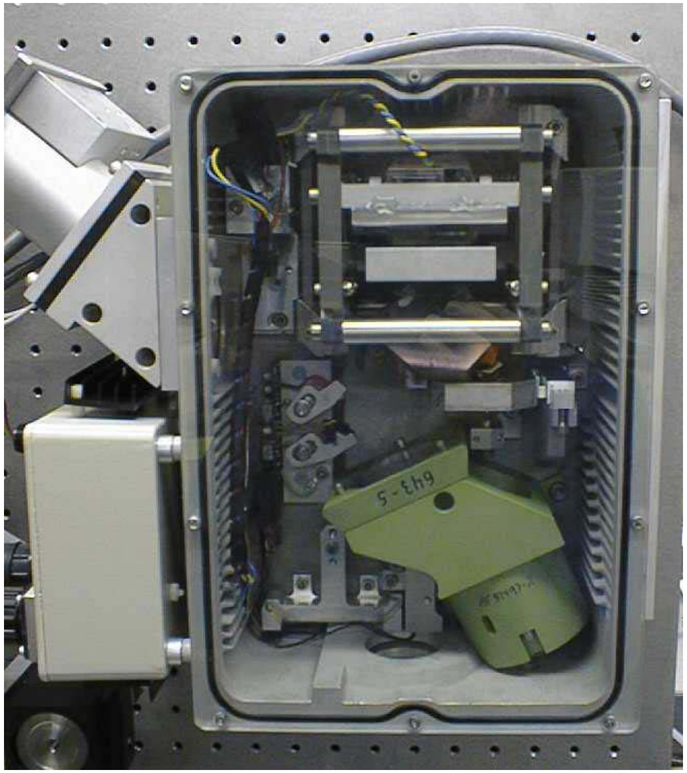
Why FTIR?

Mid IR Spectroscopy is sensitive to:

- Layer Thickness
  - “Standard” optical metrology
- Doping Concentration
  - Epi Silicon, optoelectronics
- Vibrational Modes
  - Materials **Composition**
  - For both Films and Gasses!

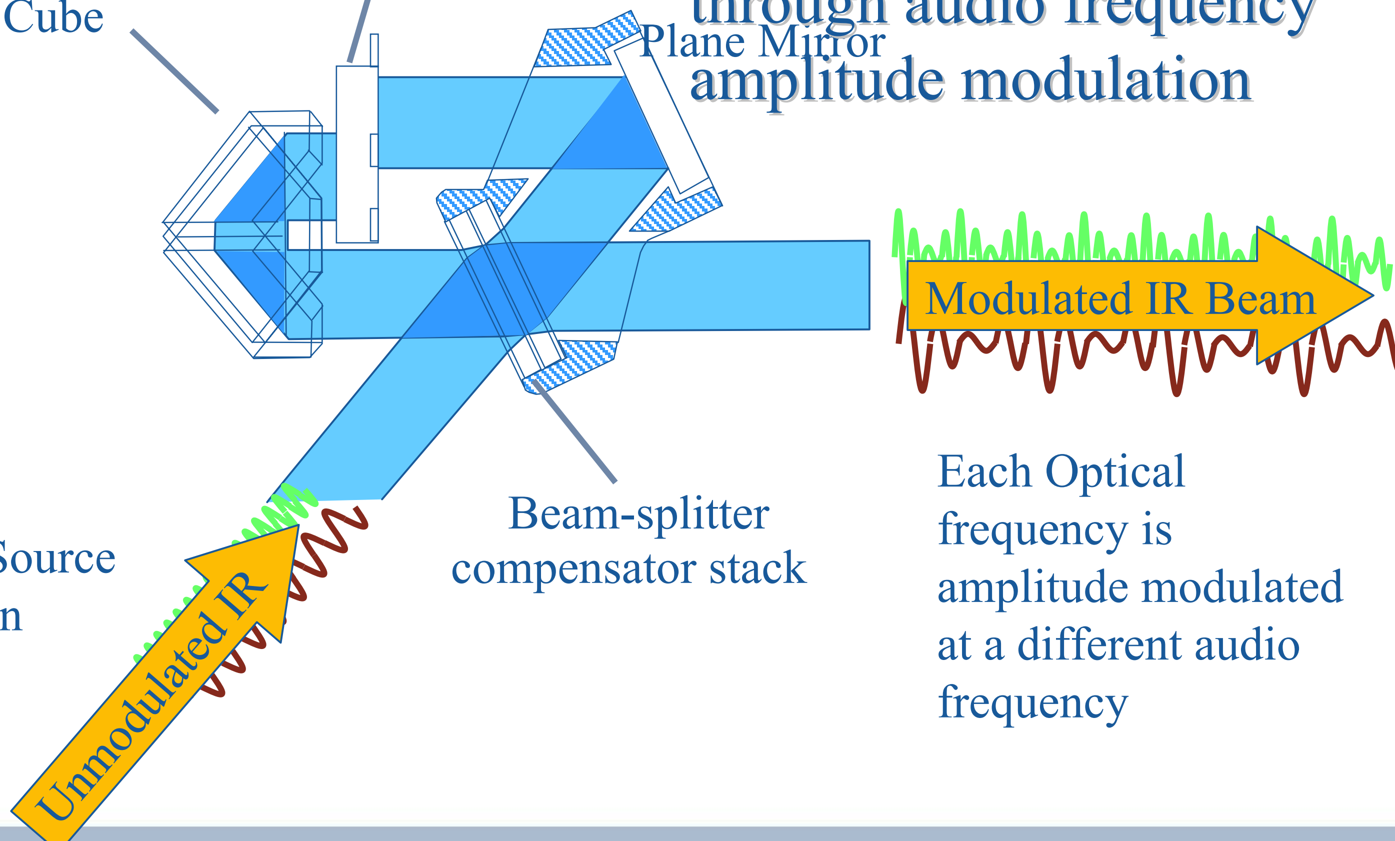
Modern Process FTIR Interferometers

Rugged, Stable, Multipurpose.



FTIR Operation

Spectral data is encoded through audio frequency amplitude modulation



Each Optical frequency is amplitude modulated at a different audio frequency mks

Technology for Productivity

Thin Film Metrology

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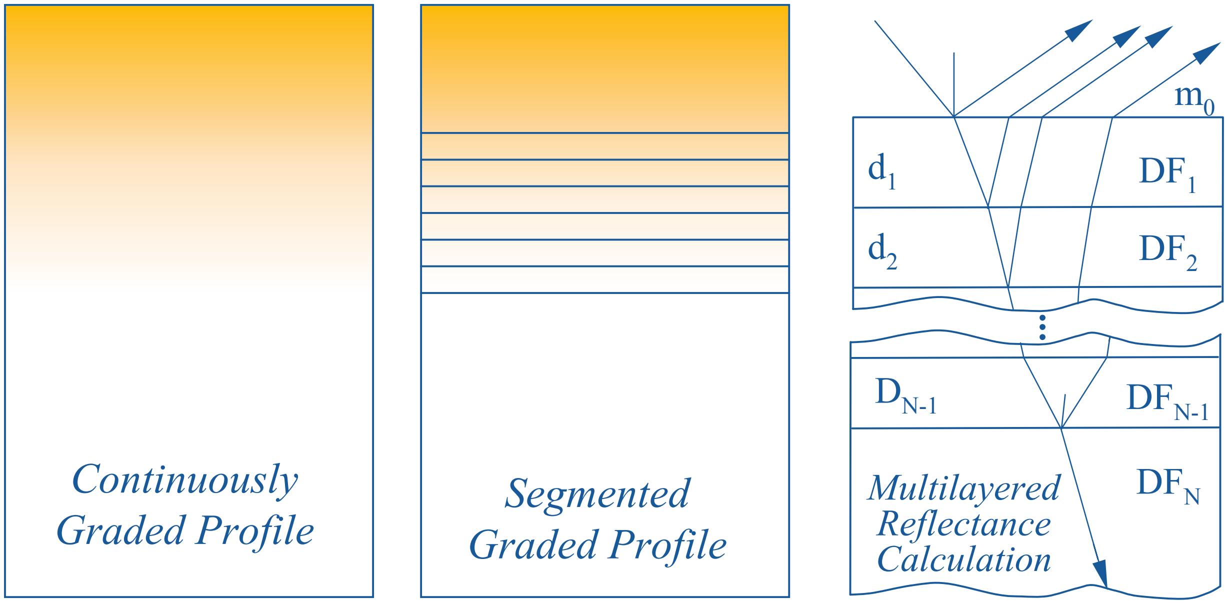
Reflectance from a Film Stack



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Recent Innovations

OLT Advances

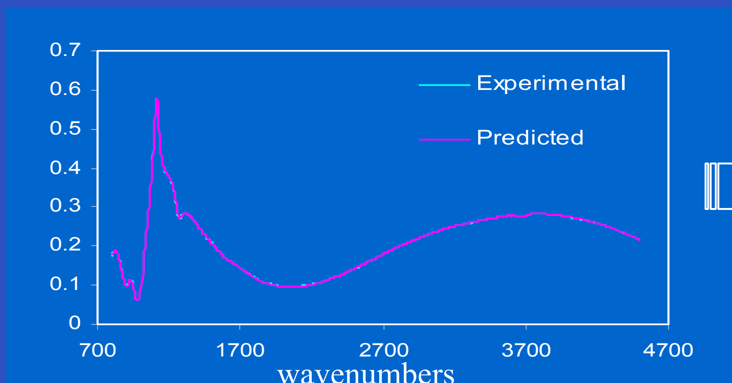
- *k*-space analysis
  - *Independent of "t"*
  - *Smaller training set*
- High Throughput Optics
  - *Small (<<1mm) spot size*
  - *~ 1 second per point*
  - *No backside artifacts*
    works with any substrate
- Modeling Advances
  - *Multivariate Chemometric Modeling*
    - FSG (easy)
    - BPSG (harder)

Other Industry Advances

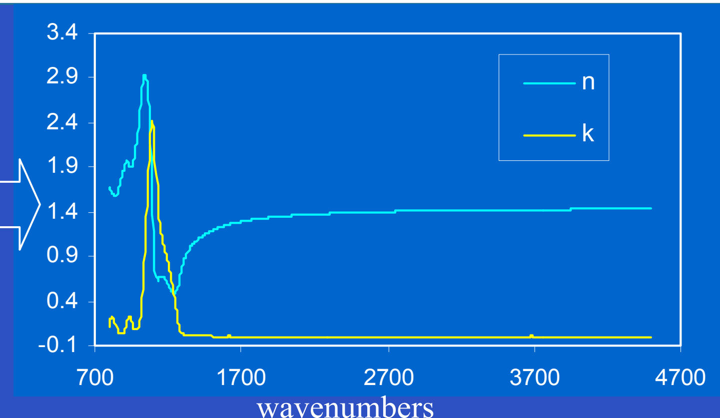
- *R*-space analysis
  - *"t", "n" & "k" convolved*
  - *Larger training set*
- Hardware Advances
  - *UV, IR & ellipsometry combined*
  - *Special chuck for low doped wafers*
    NOT applicable to any substrate.
- Modeling Advances
  - *Neural net front-end*

Illustration of FilmExpert Application™

Composition of Fluorinated Silica Glass

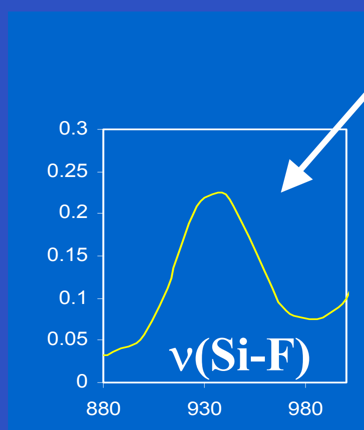


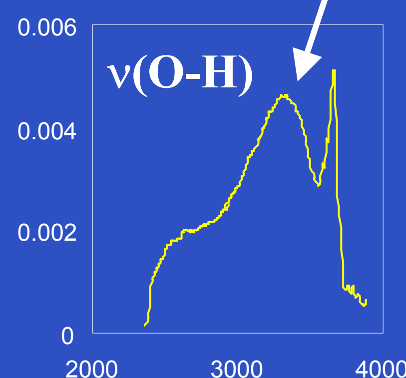
Measure Reflectance



Fit FSG film thickness & n and k

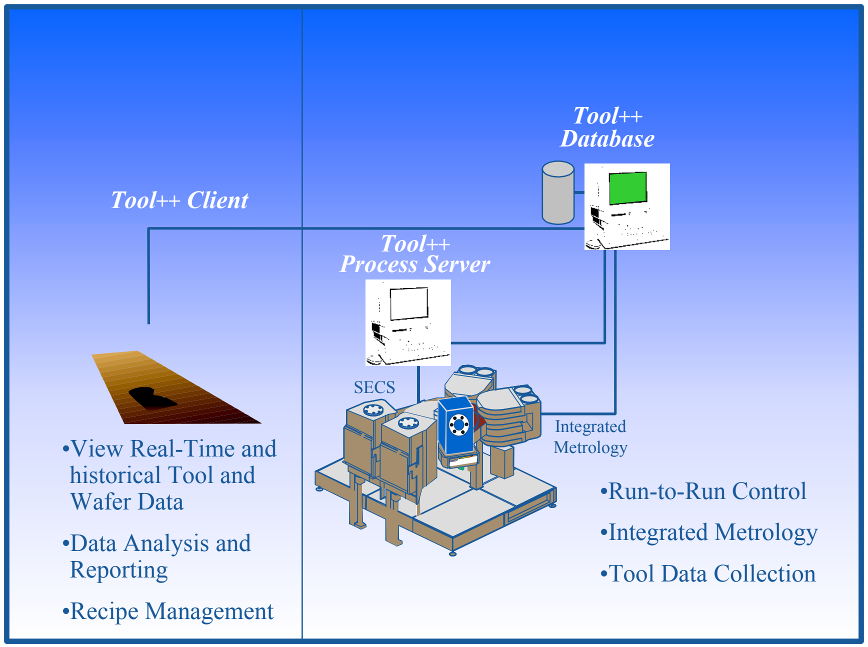
Calculate Fluorine concentration

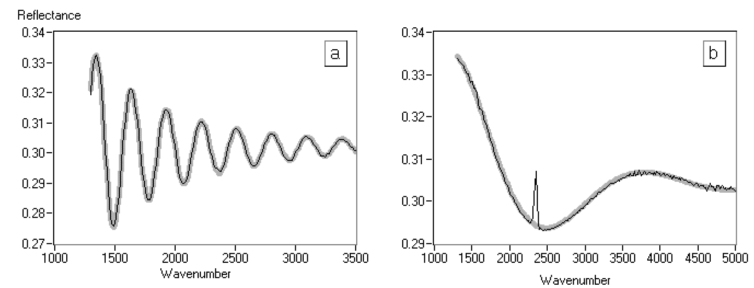




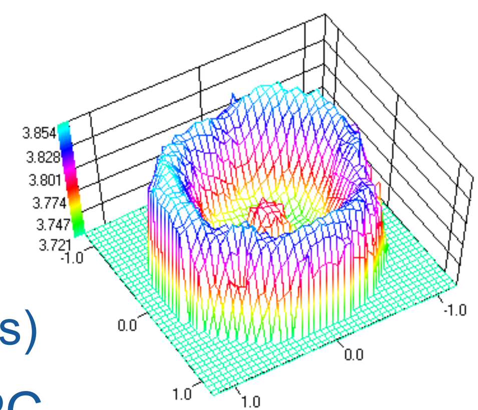
Calculate moisture and OH concentration

Film Example 1: Epi Si





5 Micron Epi 0.6 Micron Epi



- "Standard" IR Metrology Application
  - Exploits sensitivity to Free Carriers (Active Dopants)
- Deployed from stand alone, to integrated with APC.

Film Example 2: FSG Composition

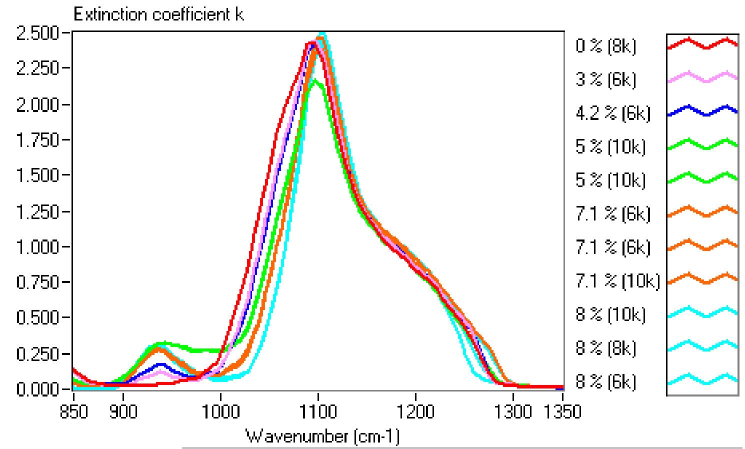
Measures:

- FSG film thickness
- FSG film dielectric function (or n and k)

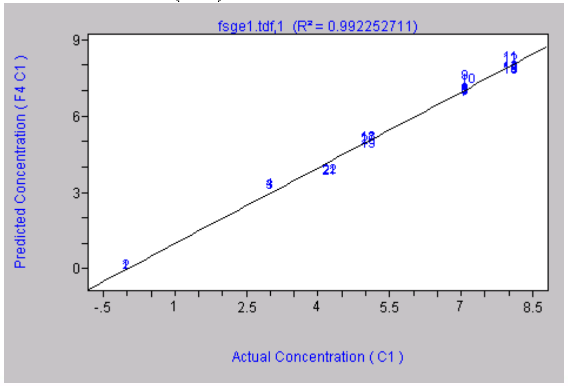
Extracts from the dielectric function:

- %F concentration
- moisture concentration

Extracted extinction coefficient k for a set of various FSG films

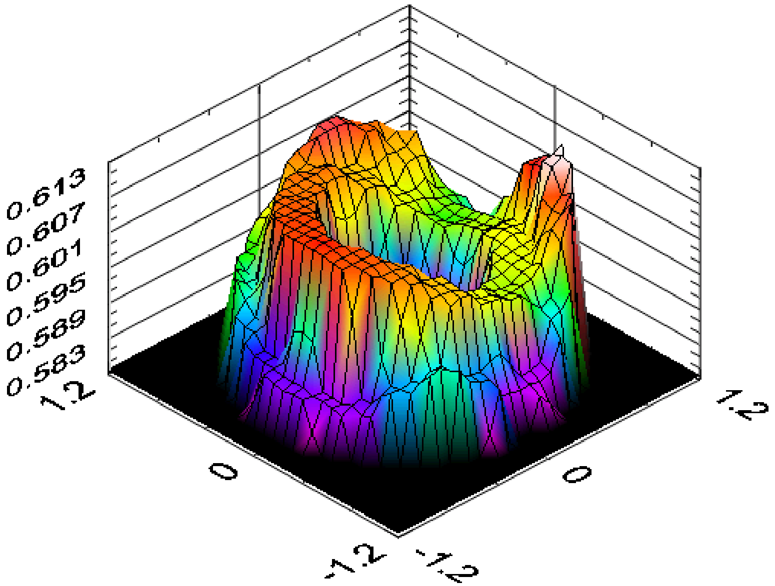


Predicted vs nominal %F concentration

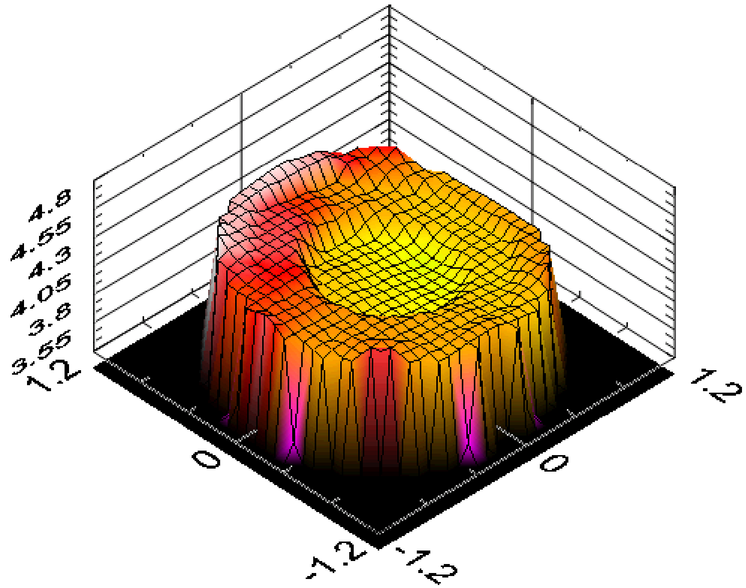


Fast Mapping Capability

Thickness Map

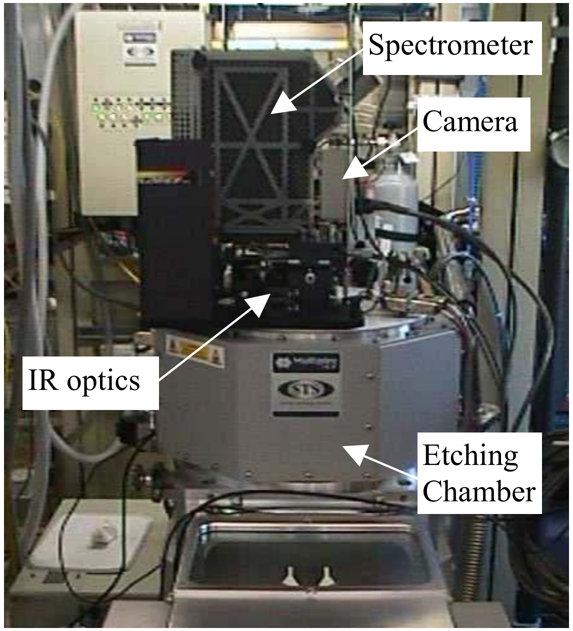


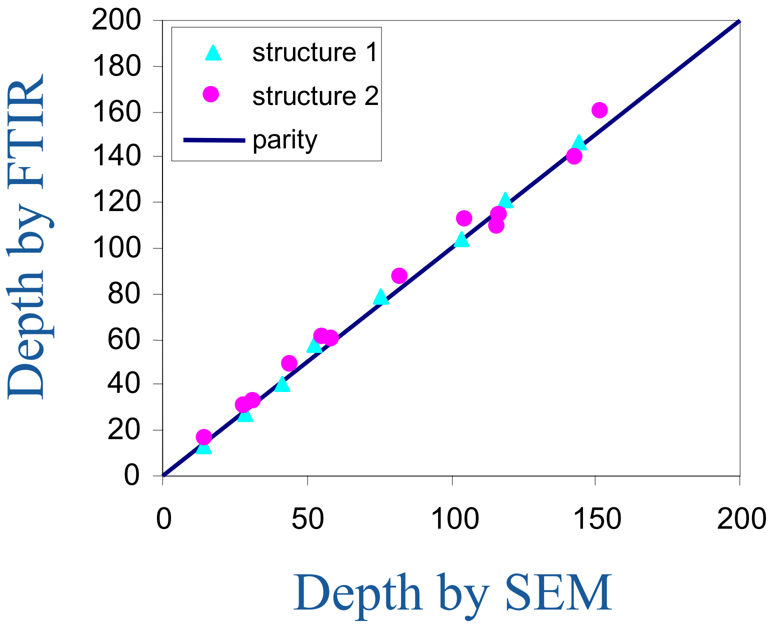
Fluorine Map



(Nominal 600 nm, 4.2 wt% F)

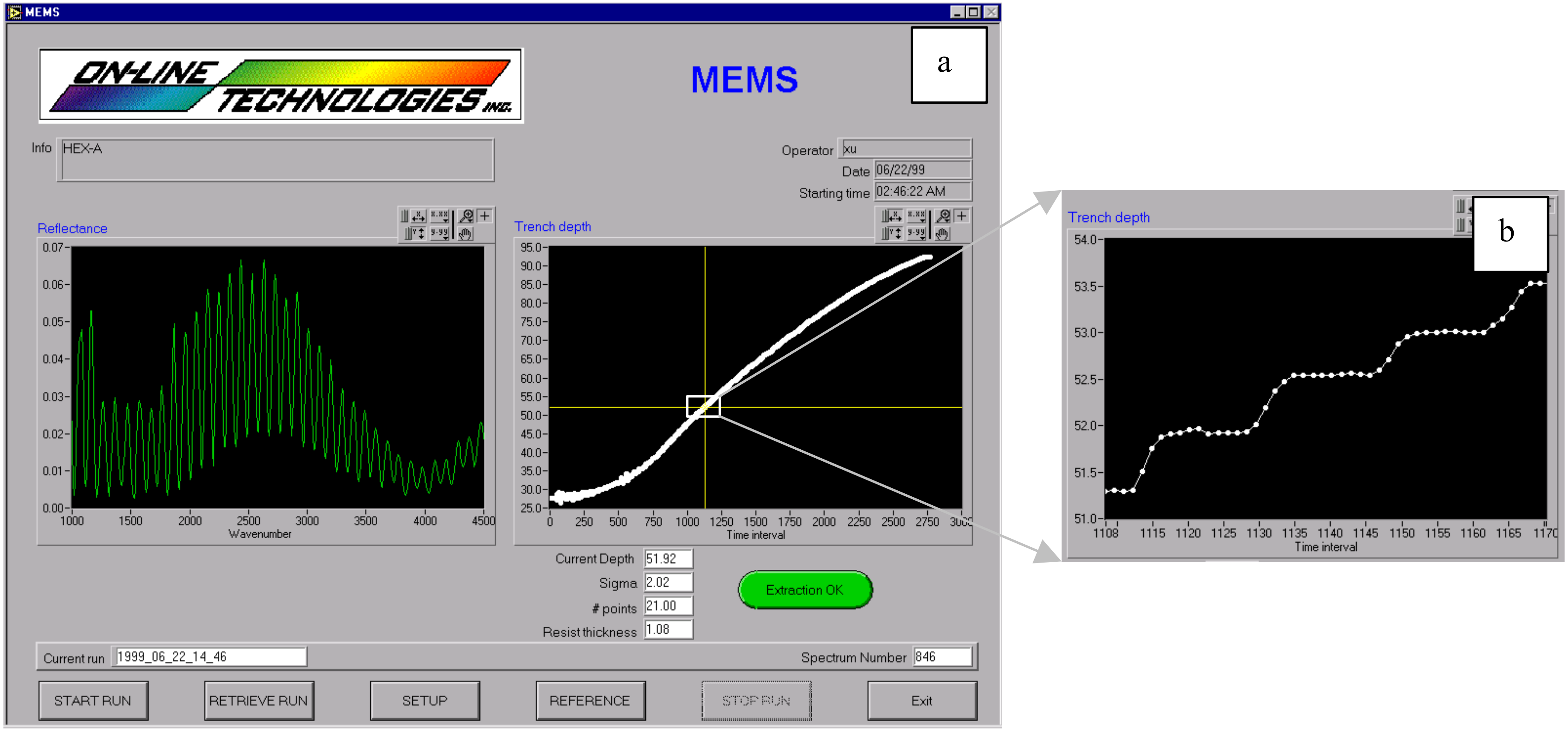
Film Example 3: in-situ MEMS



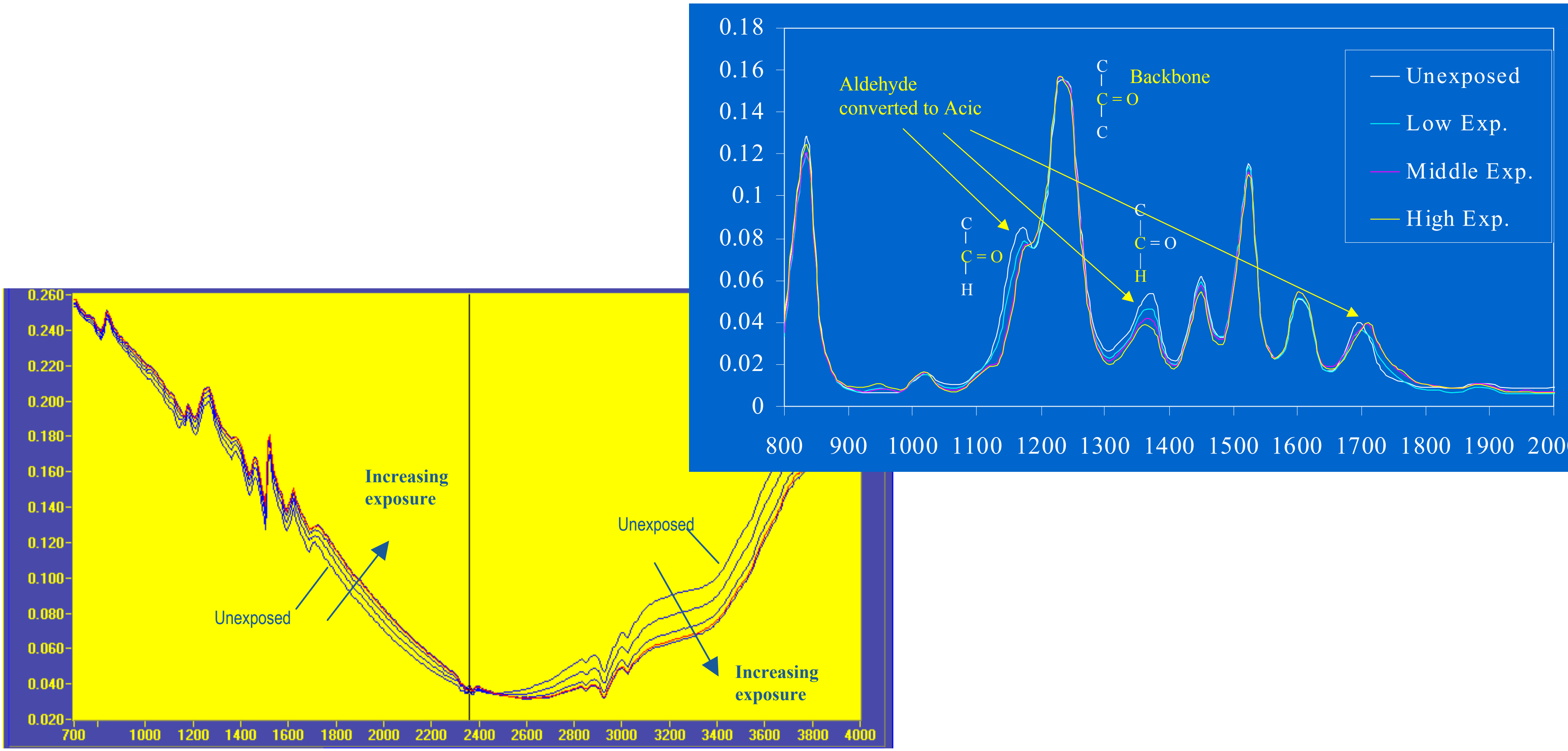


- Difficult Because
  - Long working length: greater than 12”
  - Active Plasma Present: Changing Background Light
  - Large Etch Depths: Can be Several Hundred Microns

In-Situ, Real-Time Measurement of Etch Depth



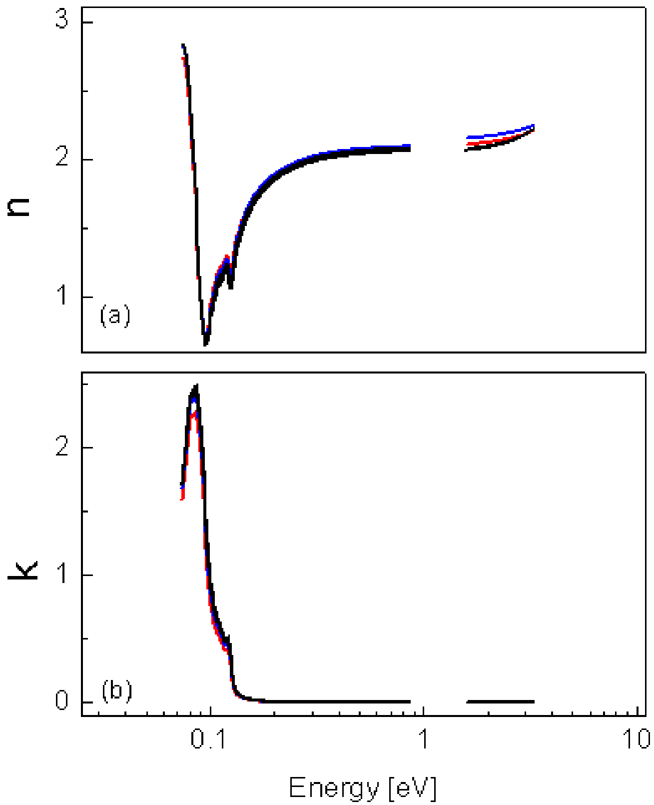
Film Example 4: DUV Resists



- Chemically complex films are ideal for IR metrology.

Film Example 5: TaO (VIS-IR combo)

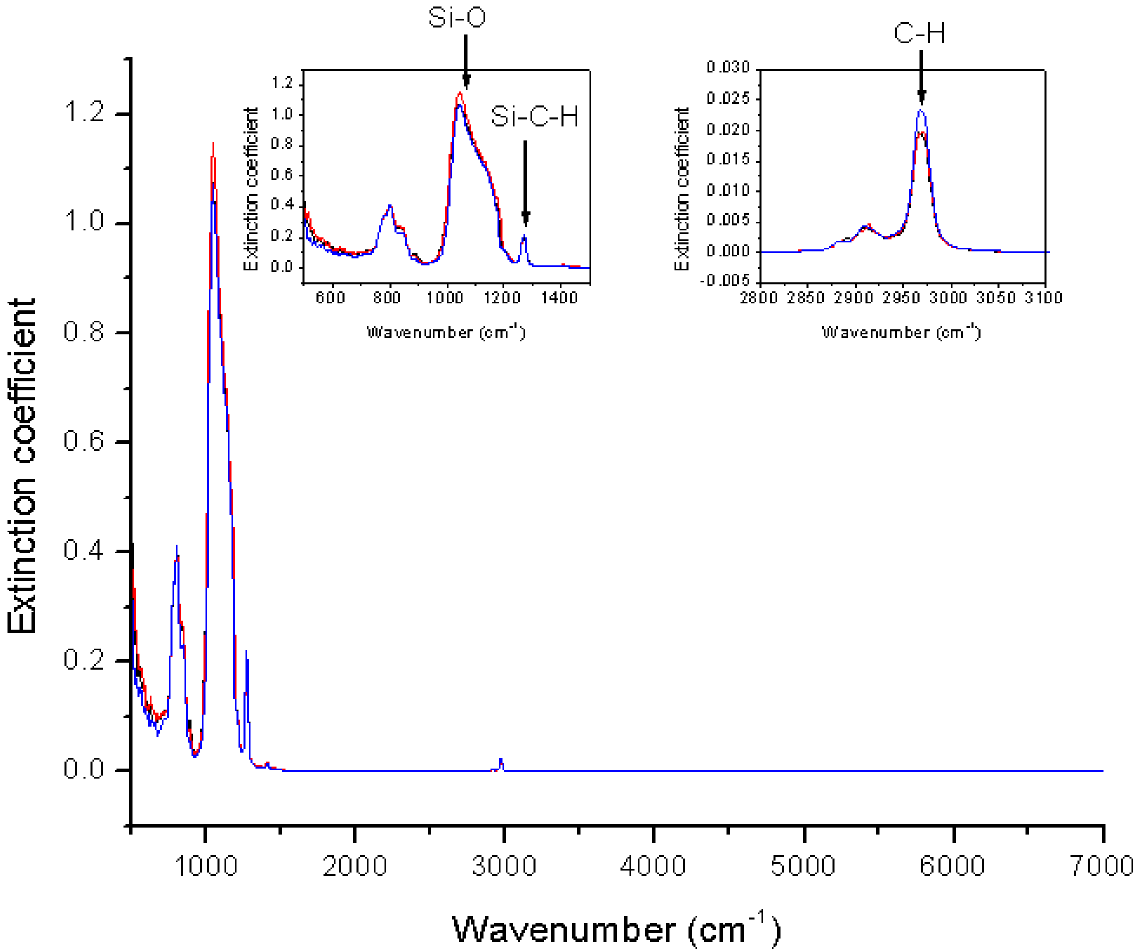
- Needs:
  - Spectral n & k is usually measured in visible / UV range
  - IR range provides useful information on molecular absorption, related to composition
  - FilmExpert™ measurements performed both in the IR range (20-1.7 micron) and visible range (380 – 800 nm)
- Results:
  - VIS level thickness accuracy with IR derived compositional information.



Film Example 6: C-doped Silicon Dioxide Films

- Carbon concentration is the key parameter to be measured
- Standard FTIR measurements are performed in transmission on high-resistivity, double-side polished test wafers
- Standard FTIR measurements only measure composition, not thickness
- FilmExpert™ measurements can be performed on actual product wafers, and extract the composition information as well as film thickness

C-doped Silicon Dioxide Films – Results



Carbon concentration determined from the extracted extinction coefficient spectrum, which is independent of thickness

Thickness extracted from the interference fringe in the reflectance spectrum

Film Summary

- New levels of chemical complexity are requiring direct access to compositional information.
- IR metrology is ideally suited for compositional measurement due to the bond-level specificity of vibrational spectroscopy.
- IR measurement techniques can be integrated into fabrication equipment for automated control of critical processes.

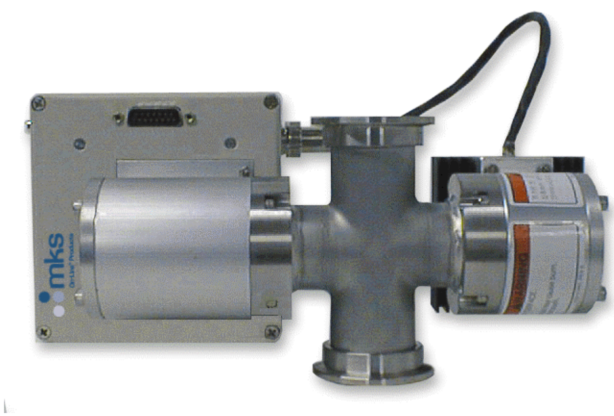
Gas Composition Analysis

- The Products
  - Filter Based and Full Spectral Instruments
- Gas Phase Specifics
  - Molecular Structure, IR Activity & Rotational Fine Structure
- Applications
  - Abatement: Scrubber Efficiency
  - Trace Detection: Feed Gas Purity Analysis
  - Chamber Effects: First Wafer and Chamber Wall
  - Process Control: Chamber Clean Endpoint

The Products

- Full Spectral Instruments (FTIR Based)
  - Use for simultaneous quantification of multiple gasses.
  - Use when flexibility of detection is a requirement: (Process Diagnostics & Development).
  - Required if different gasses overlap excessively.
- Non-Dispersive Instruments (Filter Based)
  - Use when only one gas needs to be tracked.
  - Use when size is a constraint.
  - Use when cost is a constraint.

Current Product Family



ProcessSense™

Application Specific, Single Gas Partial Pressure Sensor

MultiGas™ 2030

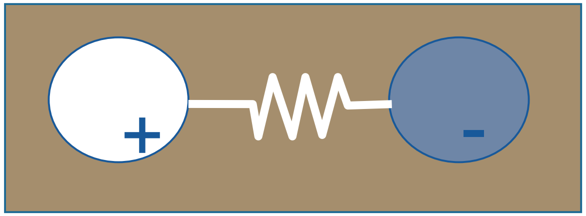
All-purpose gas analyzer.
2030p: Continuous gas purity analyzer

MultiGas™*MPX*

Multiplexed Gas Analyzer

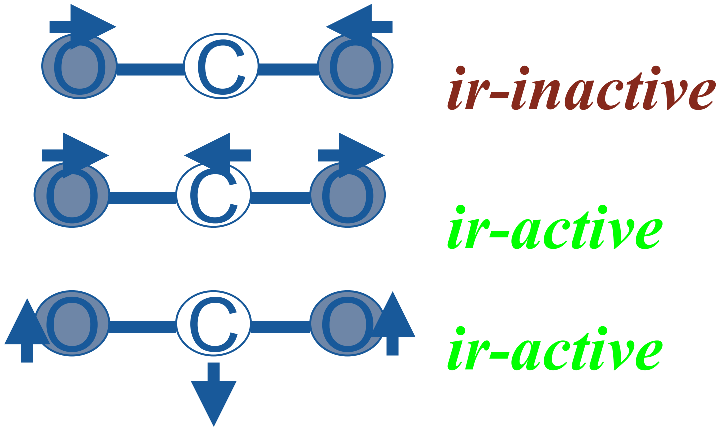
Gas Phase Spectroscopy

- Molecular Vibrations.
  - All molecules, and portions of molecules, vibrate.
  - Radiation will interact with vibrating molecules via a dipolar interaction.
  - Energy will be absorbed when the frequency of the radiation matches that of the molecular vibration.
  - A molecule can be visualized as several weights (the atoms) connected by springs (the bonds).
  - This system can be understood in a classical Hooke's Law context: the frequency depends on
    - the mass of the atoms
    - the strength of the bonds



Light and Matter

- EM radiation *(i. e., light)* has a magnetic and an electric field.
- The electric field can interact with the electrons of a molecule, and with a permanent or induced dipole.
- Molecular vibrations which cause a change in dipole moment are infrared active.



Gases not Measured by Infrared Spectroscopy

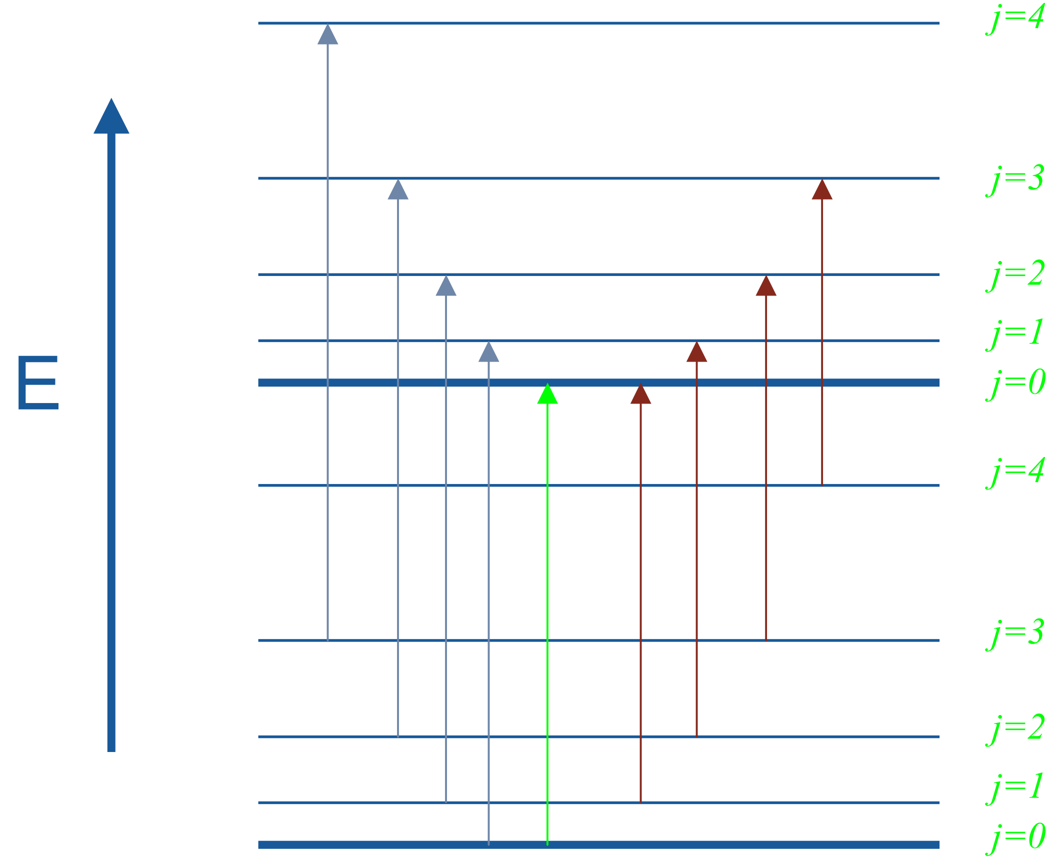
- Oxygen - O_2
- Nitrogen - N_2
- Hydrogen - H_2
- Argon -Ar
- Neon -Ne
- Chlorine - Cl_2
- Fluorine - F_2
- Bromine - Br_2
- Helium - He

Gases Measured By Infrared

Everything Else!

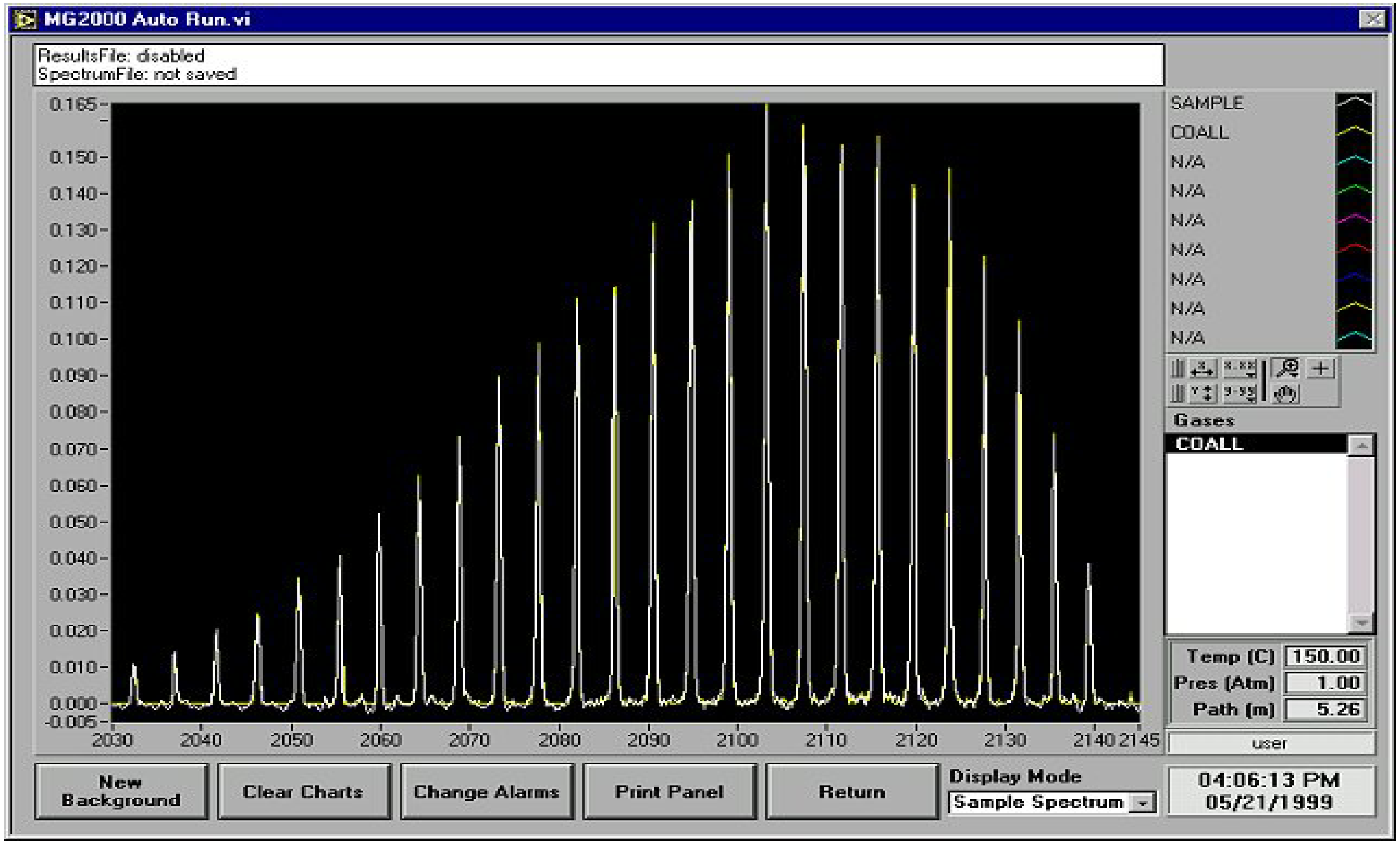
Rotational Fine Structure

- An infrared interaction may involve not only a vibration, but also quanta of rotation.
- Rotational level distributions are *molecule-specific!*
- Population distributions depend on experimental conditions.

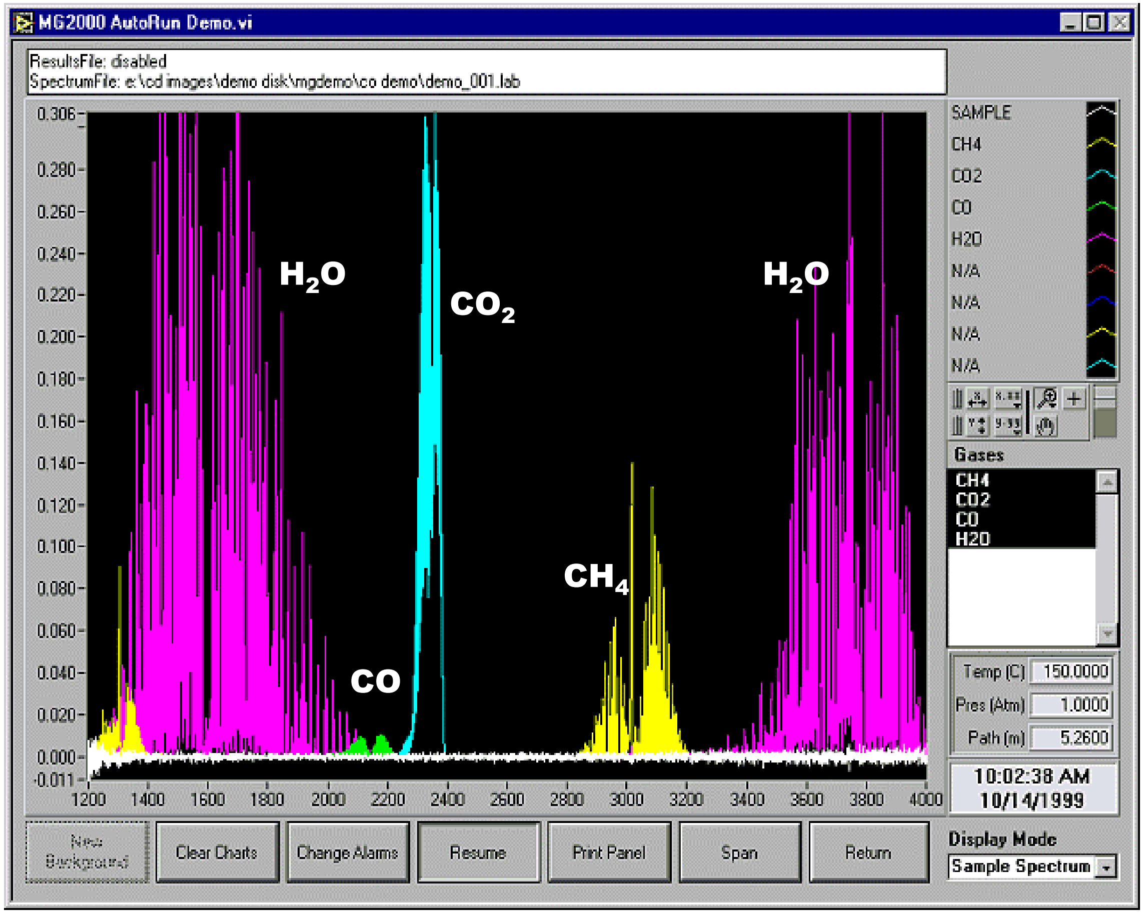


(energy levels not to scale!)

Carbon Monoxide Spectrum



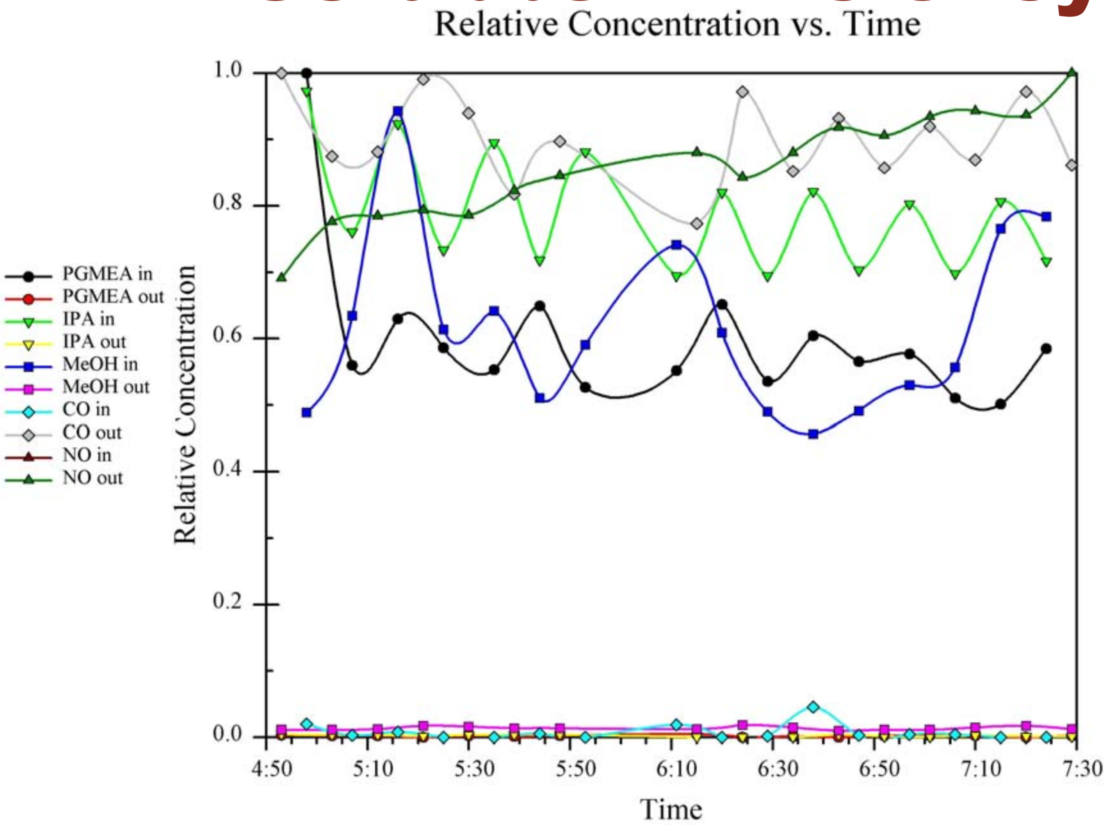
Gas Mixture Analysis



Gas Example 1: Scrubber Efficiency

- By the time the gas makes it to the scrubber, the gas mixture is complex.
- Reactions can occur in the exhaust lines, making the analysis more complex.
- This application uses two MultiGas systems, one before and one after the scrubber.
  - This is to capture fast transients.
- All IR active species can be accounted for.

Scrubber Efficiency

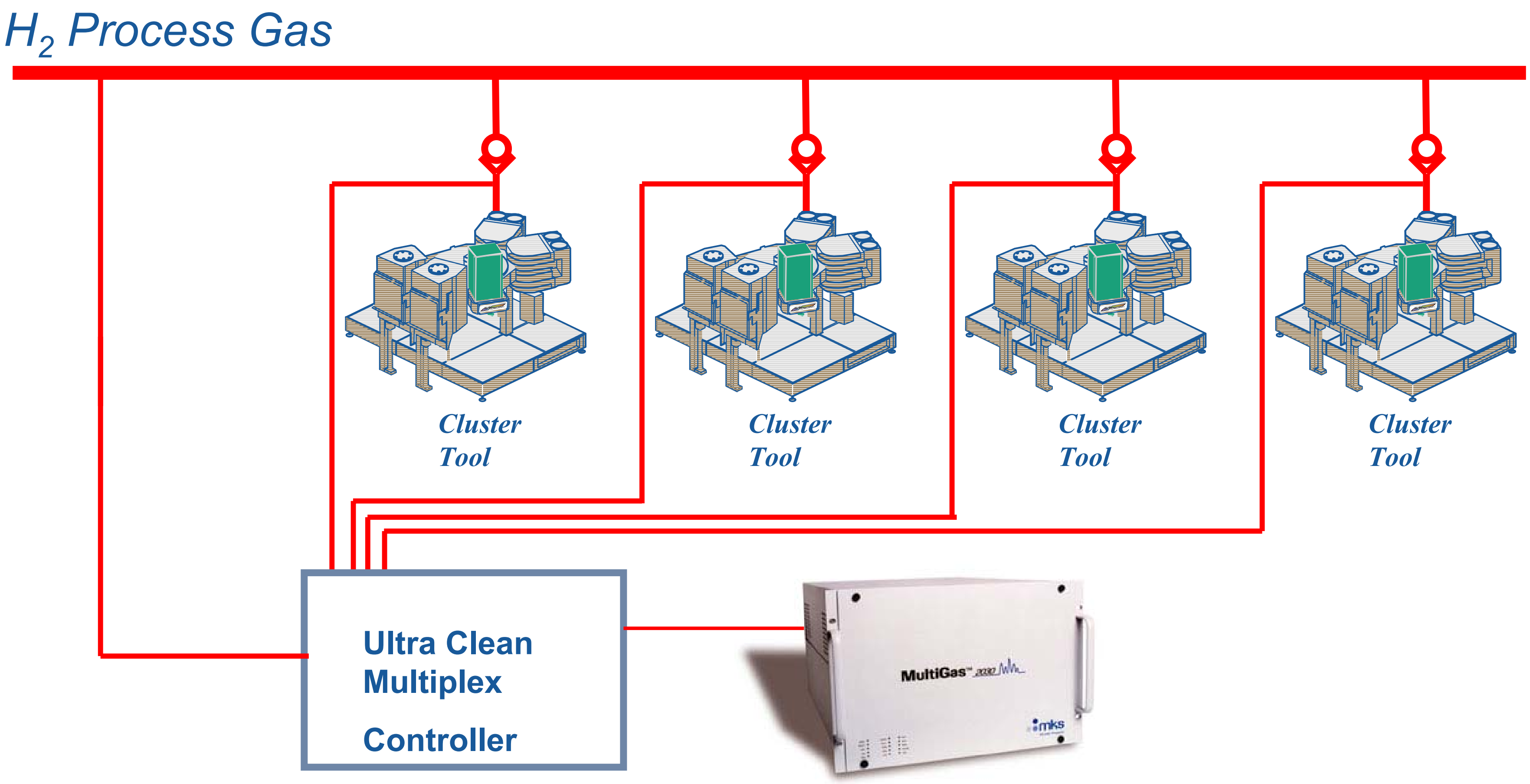


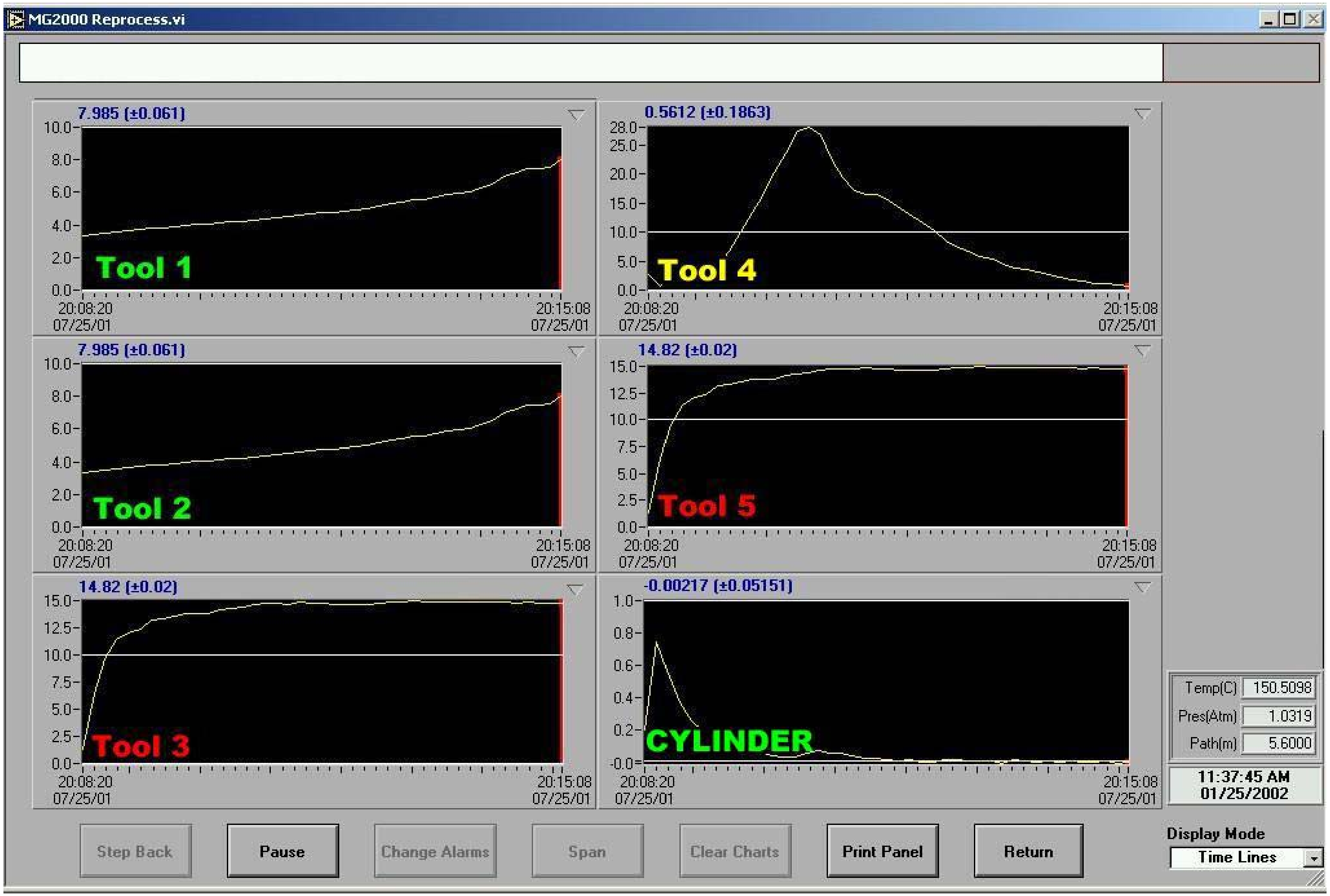
- This technique can measure efficiency, load and mass released to atmosphere (mass not scrubbed).

Gas Example 2: Feed-gas Purity.

- Several processes (like GaN LEDs) are ultra sensitive to moisture in the ammonia. High PPB levels of contamination can ruin yields.
- Ultra-low detection levels require special instrument construction.
  The MultiGas 2030p is designed specifically for sampling ultra-pure feed lines.
- Low PPB moisture detection demonstrated in NH_3 and NF_3, other gasses under development.

Gas Sampling for Several Cluster Tools



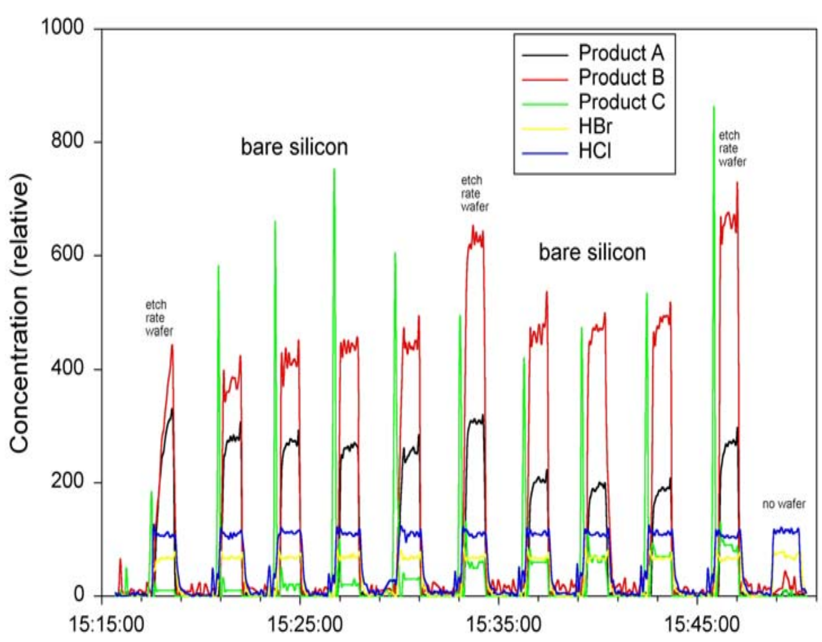


MG2000 Reprocess.vi
7.985 (±0.061)
Tool 1
0.5612 (±0.1863)
Tool 4
7.985 (±0.061)
Tool 2
14.82 (±0.02)
Tool 5
14.82 (±0.02)
Tool 3
-0.00217 (±0.05151)
CYLINDER
20:08:20
07/25/01
20:15:08
07/25/01
Temp(C) 150.5098
Pres(Atm) 1.0319
Path(m) 5.6000
11:37:45 AM
01/25/2002
Step Back
Pause
Change Alarms
Span
Clear Charts
Print Panel
Return
Display Mode
Time Lines

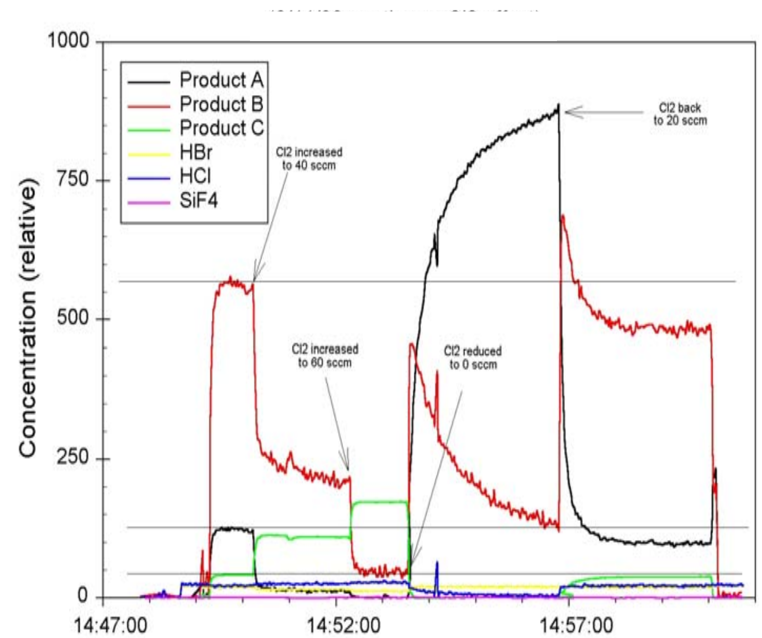
Gas Example 3: Process Diagnostics

- The process effluent contains significant process information.
  - For dep, it's what's put in the chamber less what's left on the wafer.
  - For etch, it's the gas introduced into the chamber plus what's been removed from the wafer.
- Because the measurement is after the tool, it is non-invasive and won't shift the process.
  - People don't worry about the exhaust line, but do worry about the feed lines and chamber integrity.
- Can be like abatement example, quantifying emissions and green house gas loading.
  - By measuring a specific tool, individual process efficiencies and mass exhausted from the tool can easily be quantified for estimating abatement requirements or emission mass.

Process Diagnostics



First Wafer Effects



Wall Chemistry Effects

- The possibilities are endless…..

Other Process Diagnostic Examples

- Gas Panel Purging and Gas Mixing
  - MultiGas technique has identified several undesirable gas mixing events during panel purge. An example is TEOS mixing with NF3, with produces particles.
- Remote Plasma Clean Process Optimization
  - Real-time observation of NF3 in the exhaust line is an indication of dissociation efficiency. An inefficient clean recipe was found and eliminated within minutes of process characterization.
- New Chemistry Process Development.
  - FTIR-based instrument used in SEMATECH EPIT for C3F8/02 clean chemistry process optimization.

Gas Example 4: Remote Plasma Endpoint

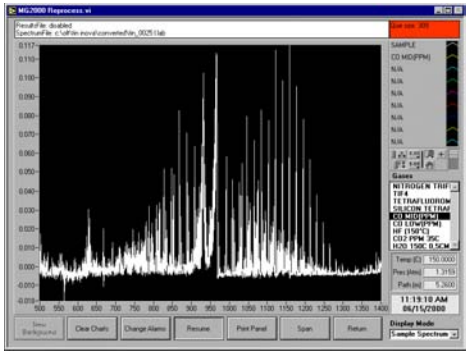
- The switch to remote plasmas for radical generation is incompatible with OES based endpoint techniques.
  - The increased clean rates of remote plasma processes have driven their adoption, but the processes are timed due to no endpoint monitor.
  - Timed processes are very inefficient, wasting gas, tool time and RF hours.
- IR Adsorption ideal technique.
  - Doesn’t require active plasma.
  - Deployable in filter based technology (low $).

Application Qualification

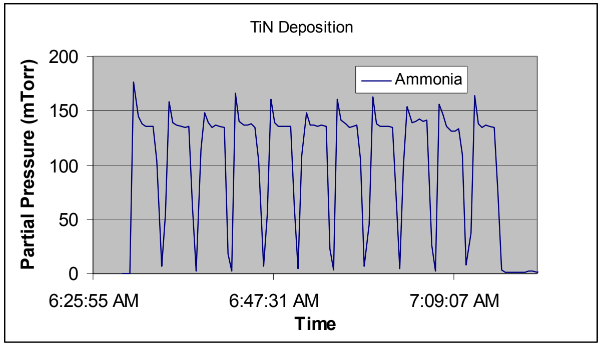
- Installed MultiGas 2010 in exhaust line.
  - 5.26 meter optics
  - KF-40 fittings
- Used by-pass to maintain conductance.
- Ran at 0.5 cm-1 resolution.
- 15 seconds averaging.

Deposition

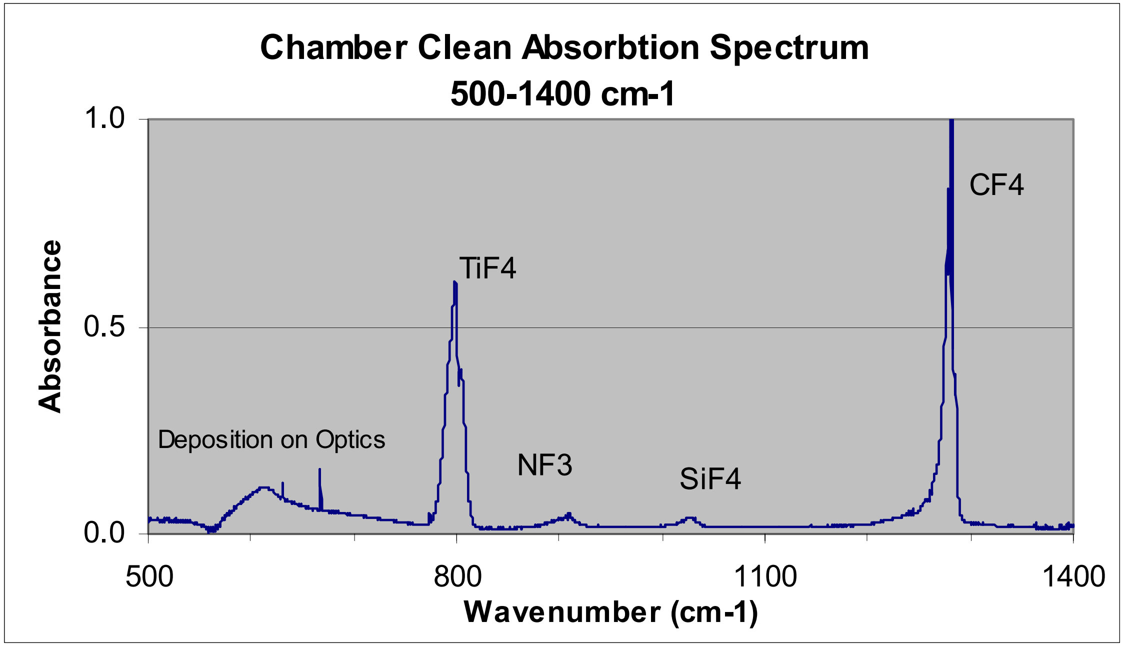
- Complex Structure.
  - Not completely characterized.



- Each Wafer Resolved.
  - Need faster update time for fault detection.

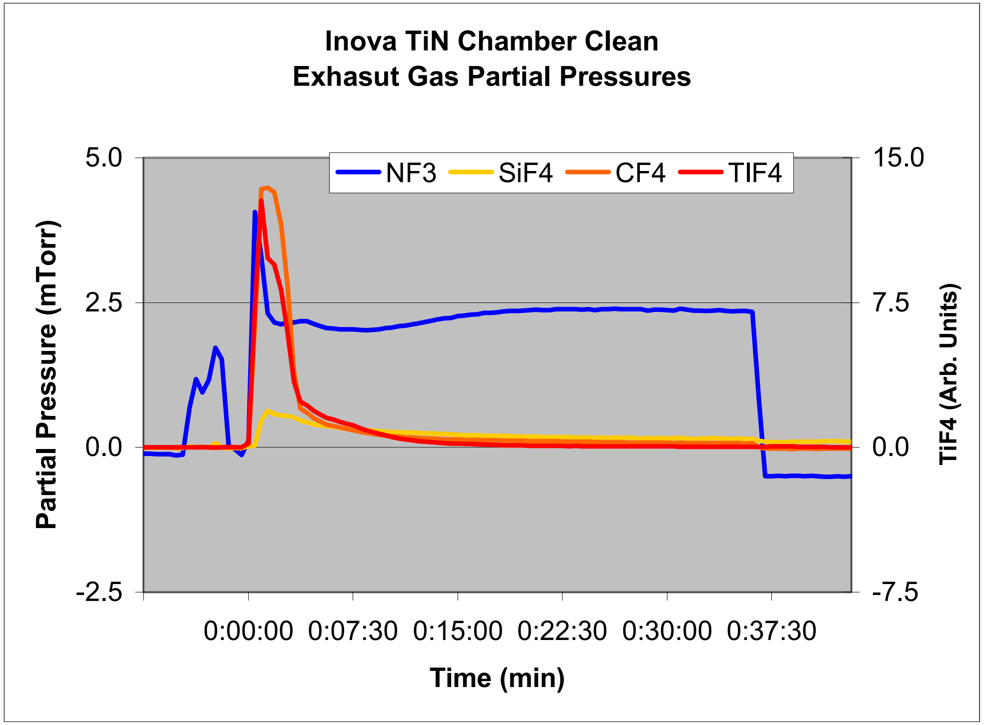


Chamber Clean Chemistry



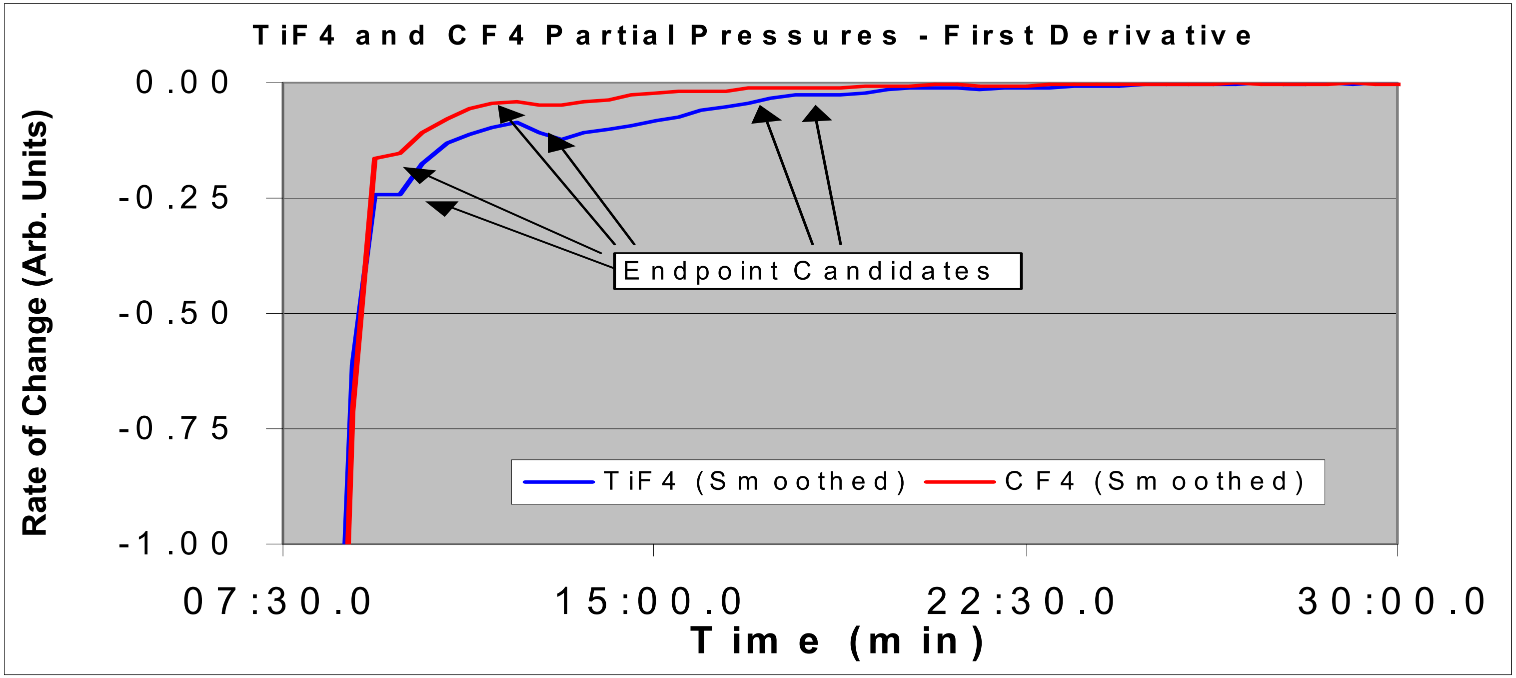
- All Components Identified:
  - NF_3, TiF_4, CF_4, SiF_4, HF, CO, COF_2

Partial Pressures vs. Time



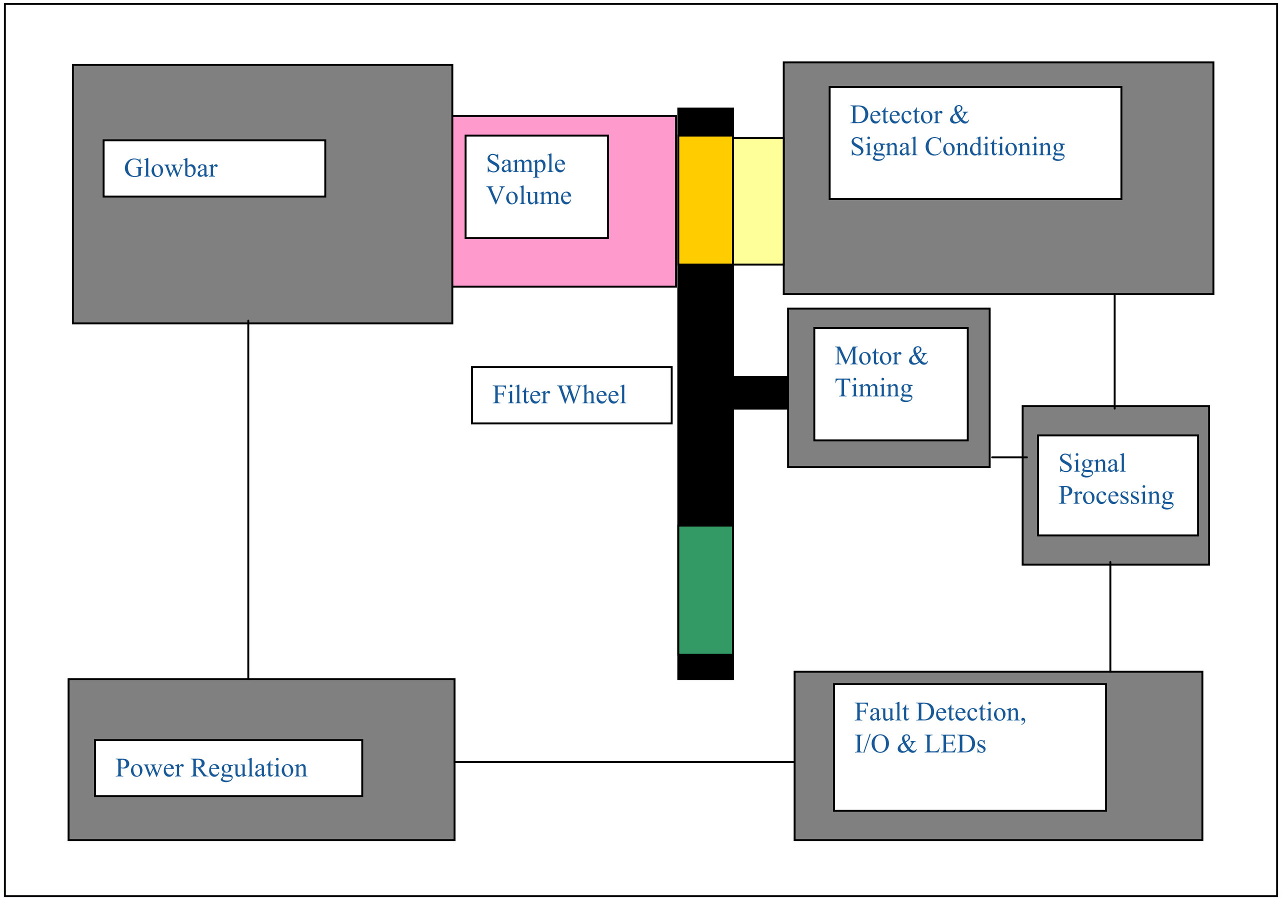
- TiF_4 and CF_4 both excellent candidates!

TiF4 and CF4 Partial Pressures First Derivative, again

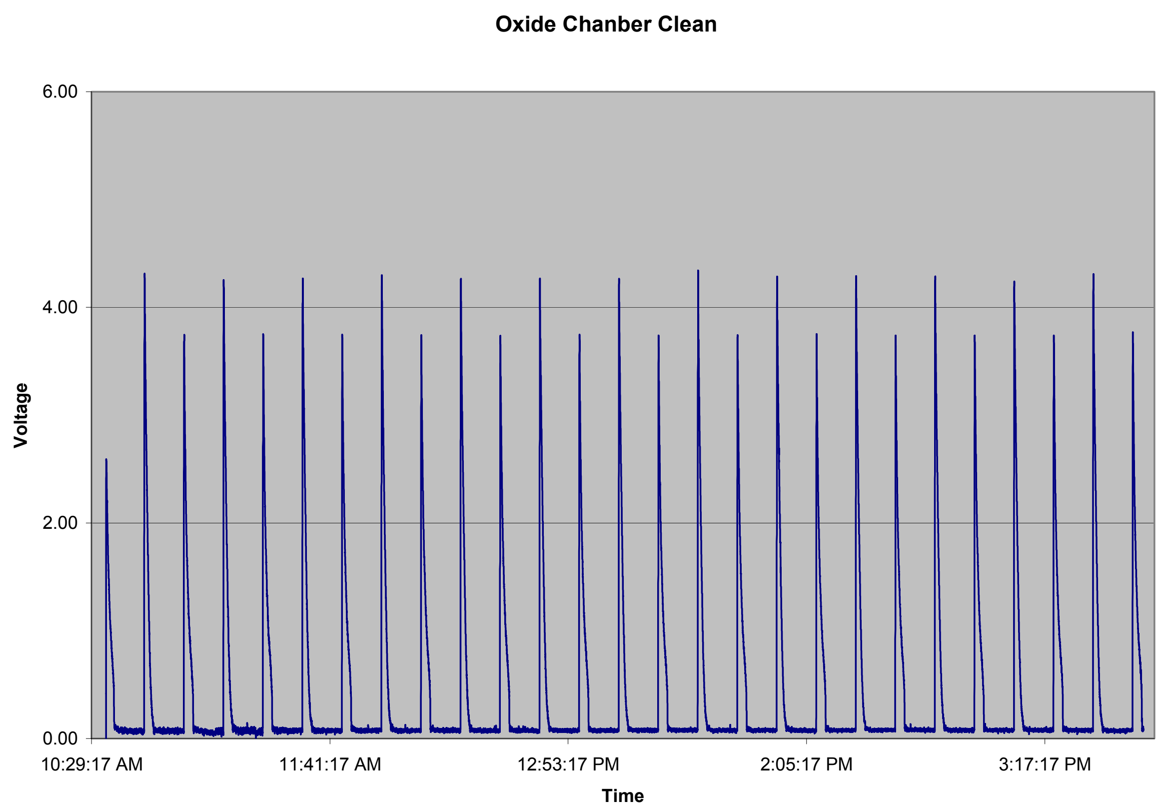


- Several Candidates Identified.

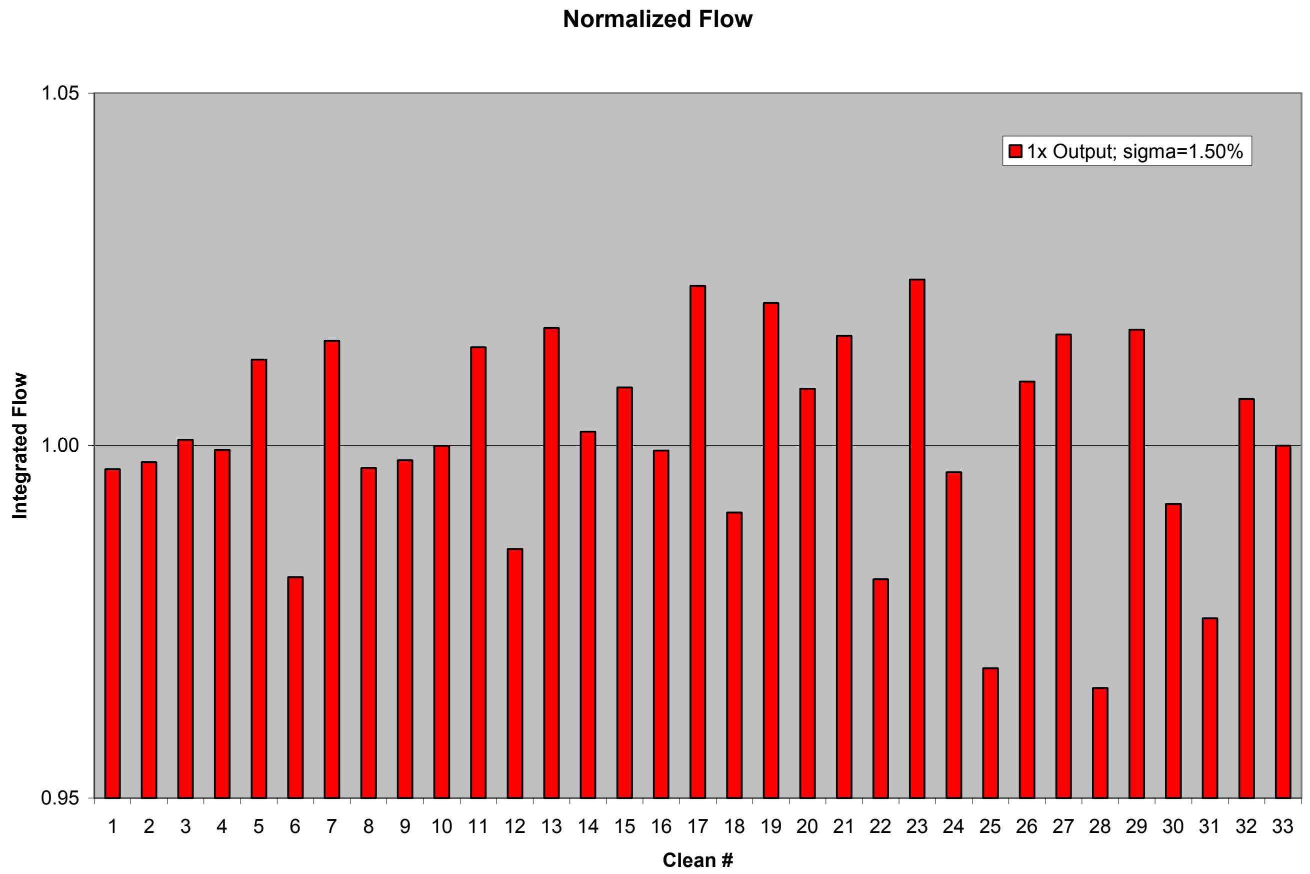
Filter-Based Sensor Theory of Operation



Observed Process Variability



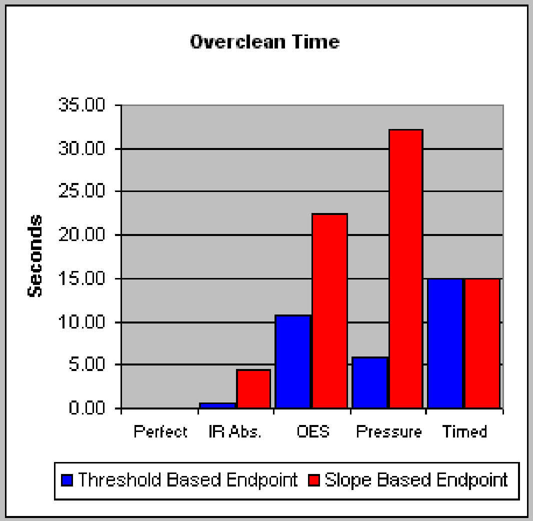
Mass Removal Repeatability

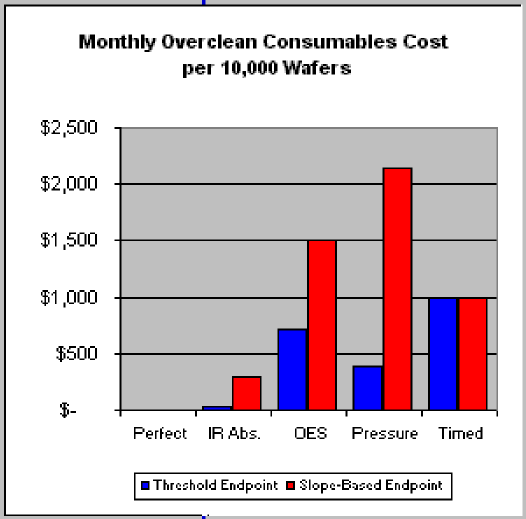


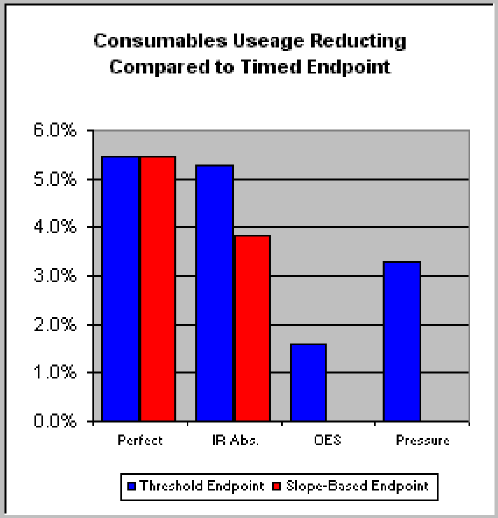
Benefits

Overclean Calculator	Perfect	IR Abs.	OES	Pressure	Timed
Value (mV)	5000	**5000**	**5000**	**5000**	n/a
Slope (mV/s)	1000	**125**	**25**	**10**	n/a
Acceleration (mV/s2)	1000	**25**	**5**	**2**	n/a
Noise (mV)	0	**25**	25	25	n/a
Sample Rate (Hz)	1	**10**	10	10	n/a
Smoothing (Samples)	1	**10**	**10**	**30**	n/a
Drift (%)	0.0%	**1.0%**	**5.0%**	**1.0%**	n/a
Threshold Time Budget	0.00	0.53	10.63	5.91	**15.00**
Slope Time Budget	0.00	4.51	22.54	32.23	15.00

Gas Flow Calculator	Perfect	IR Abs.	OES	Pressure	Timed
Ideal Clean Time	**260**	260	260	260	260
Wafers Per Clean	**5**	5	5	5	5
Wafer Starts Per Month	10,000	10,000	10,000	10,000	10,000
Consumables Cost per Liter	$ **2.00**	$ 2.00	$ 2.00	$ 2.00	$ 2.00
Consumables Flow Rate L/Min	**1.0**	1.0	1.0	1.0	1.0
Threshold Overclean Cost	$ -	$ 35	$ 709	$ 394	$ 1,000
Slope Overclean Cost	$ -	$ 301	$ 1,503	$ 2,149	$ 1,000
NF3 Savings Threshold vs Timed	5.5%	5.3%	1.6%	3.3%	0.0%
NF3 Savings Slope vs Timed	5.5%	3.8%	-2.7%	-6.3%	0.0%







Gas Analysis Conclusions

- IR Spectroscopy can be used everywhere!
  - Feed or Process Gasses, Process Diagnostics, Abatement Characterization, Stack Emission Quantification etc.
- FTIR based instruments are versatile and powerful.
- Filter-based instruments are inexpensive.
  - Application specific sensors can be deployed on every tool.
  - Process Control Strategies using filter based tools can save big $!

Final Comments

- IR Spectroscopy is here to stay!
  - The new degree of chemical complexity demands it.
- New hardware and software make the technology accessible.
  - Don’t need a PhD with each analyzer.
- No matter the application, IR can help!
  - Process Diagnostic & Control, Abatement, EH&S, facillities etc.

Thanks to everyone for the opportunity to present!