Calibrating Optical Sensors for Semiconductor Process Control

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Outline

- Integrated optical sensors for semiconductor process control
- Sources of drift and variation
- Broadband radiometric calibration method

Integrated Metrology

- Integrated measurement philosophy
  - Data now rather than later (W2W instead of L2L)
  - Integrated metrology localizes problems in real-time for greatest financial impact[1]
- What are unique challenges for integrated metrology?
- Focus on optical sensors
  - Primarily optical emission spectroscopy (OES) and reflectometry

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[1] – *Charles Weber, “Strategic Options for Users and Suppliers of APC Technology”, Integrated Metrology Association Meeting, San Francisco, CA, 1999*

Integrated Optical Sensors

- OES for endpoint detection
  - Historically interference filter or monochromator based
  - Now spectrographs and multivariate algorithms
- OES for emerging applications
  - Chamber matching[2] and fault detection[3] place new demands on OES
- Reflectometry
  - Wafer state endpoint monitor for deposition and CMP[4]
  - “Similar” hardware for scatterometry

[2] *– ISMI Equipment Chamber Matching (ECM) Project*

[3] *– H. H. Yue et al., IEEE Trans. Semi. Manu.,* ***13****, No. 3, Aug. 2000, Pg. 374-385*

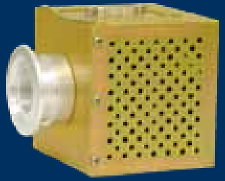
[4] *– Jeff David et al., 8th European AEC/APC Conference, Dresden, Germany, April 2007*

Verity Instruments Product Overview

Monochromator

System Controller

Spectrographs
(UV-VIS & NIR)

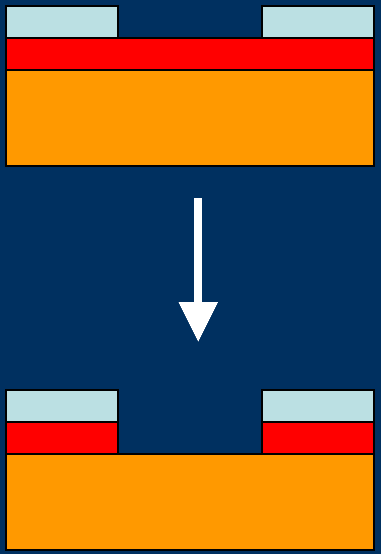


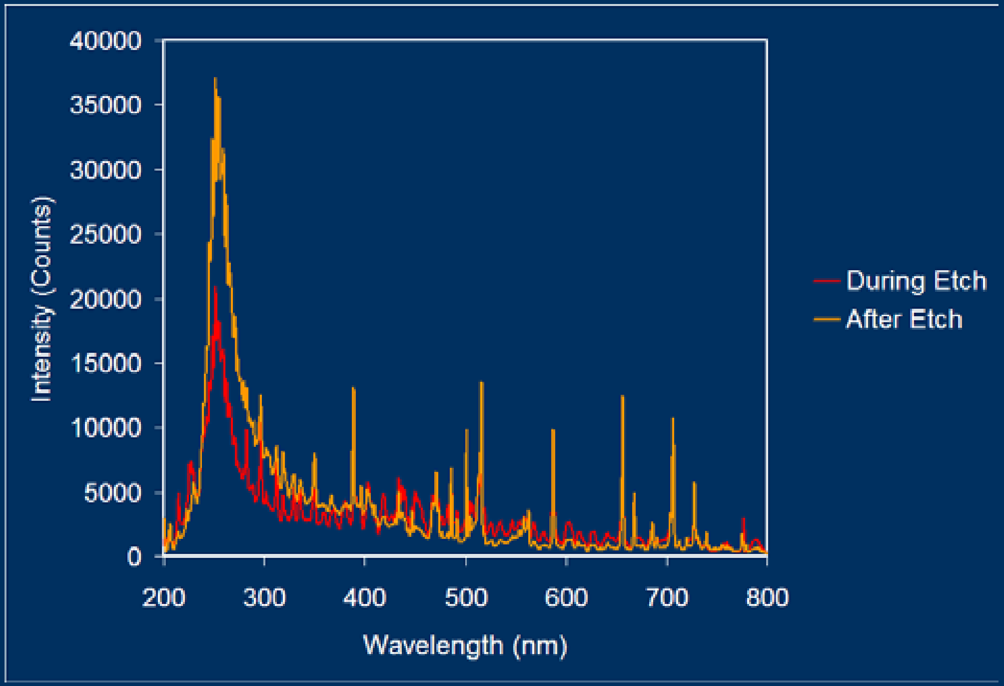
Interference
Filter Detector

System Controller

Spectral
Reflectometer

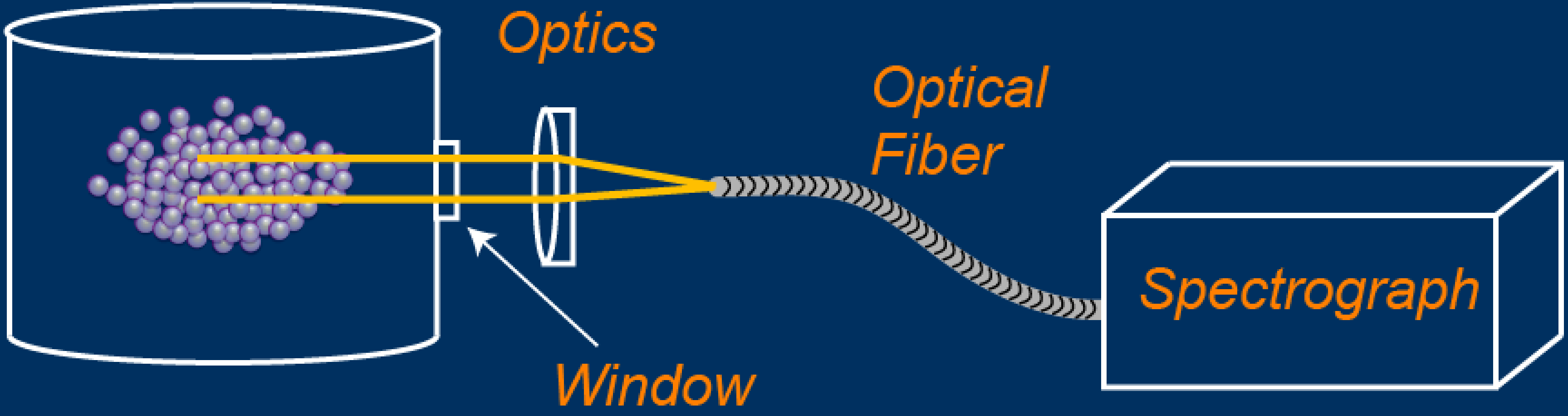
OES Endpoint





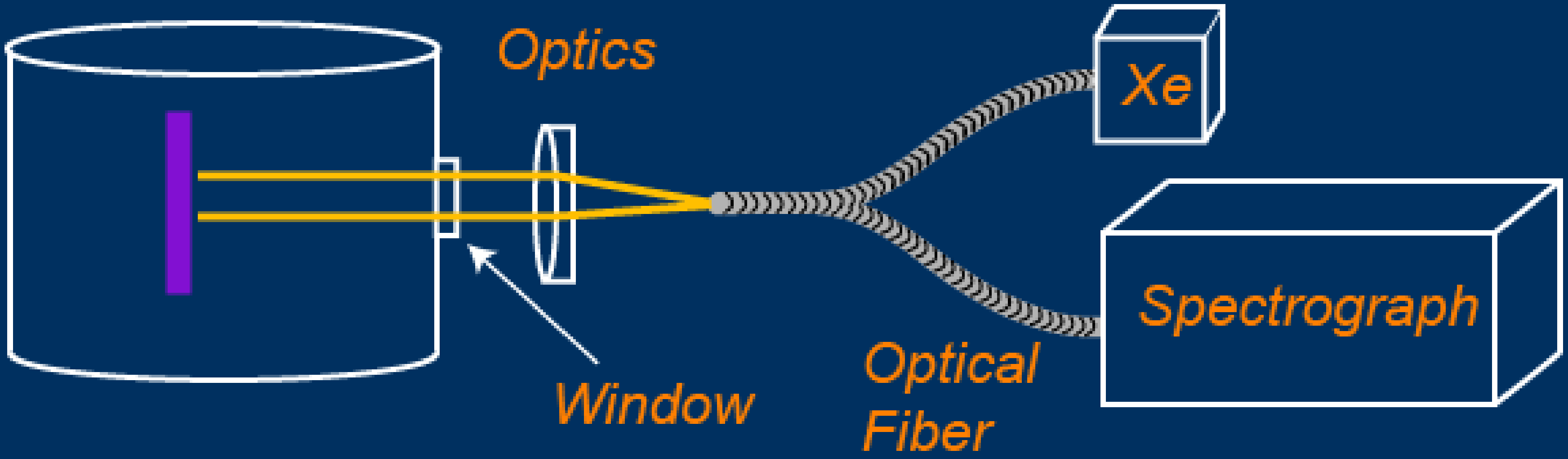
- During etch, plasma emission spectrum changes as etch layer is cleared à endpoint
- Magnitude of change depends on etch chemistry, open area, layer material, etc.

Integrated Optical Systems: OES



- Four primary sub-systems in OES path (window, optics, fiber, spectrograph)

Integrated Optical Systems: Reflectometry



- Same sub-systems as OES (window, optics, fiber, spectrograph) plus Xe flashlamp

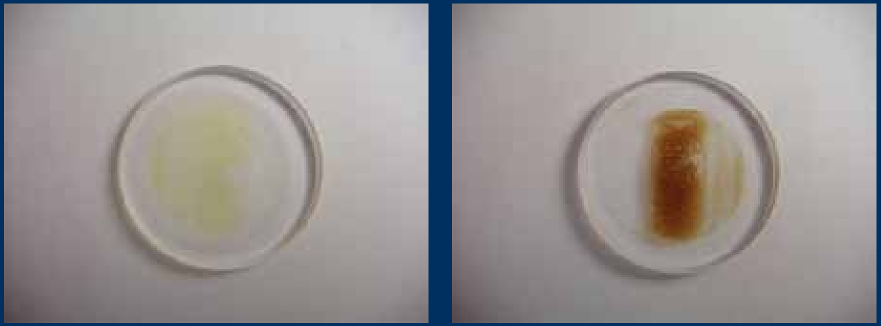
What are the Challenges?

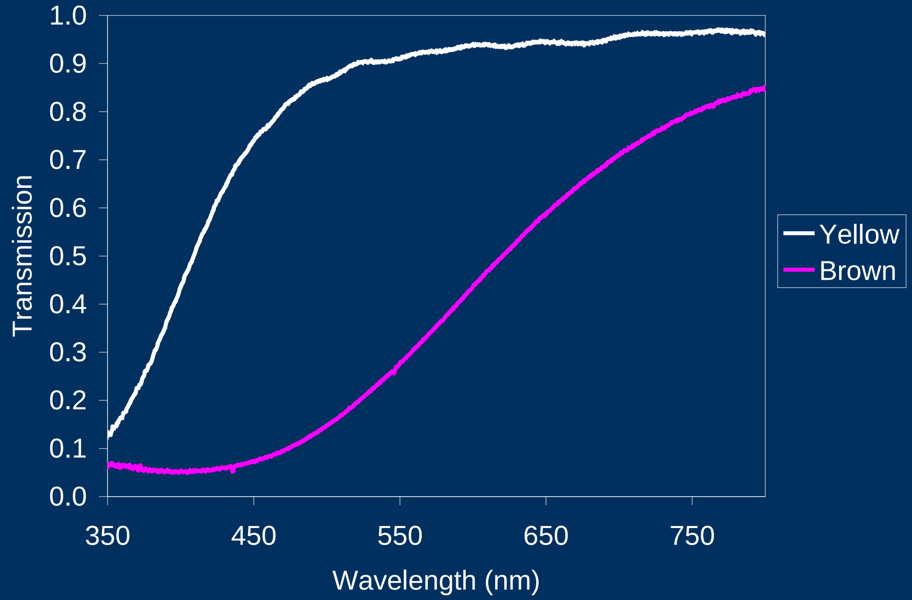
- *In-situ* environment is harder to control
  - That is, process chambers are messy (e.g. reactive chemistries, wet, hot, vibration, etc.)

  à Sources of *<u>drift</u>*
- Use of calibration standards *in-situ* can be very difficult

  à *<u>Unit-to-unit</u>* repeatability is important
- In light of all this, high gage capability is still required

Window Transmission





- Re-deposition of particulate causes clouding
  à *drift*
- Depends on chamber geometry and process
- DTransmission/DTime can approach 20%/day

Chamber Coupling Optics

- Most common are direct (no lenses) and simple focusing lenses
- Reflectometry often used with collimating lenses
- Mostly susceptible to *unit-to-unit* variations
  - – Geometric alignments
  - – Lens tolerances
  - – Broadband AR coatings (if applicable)
- Specific to each installation

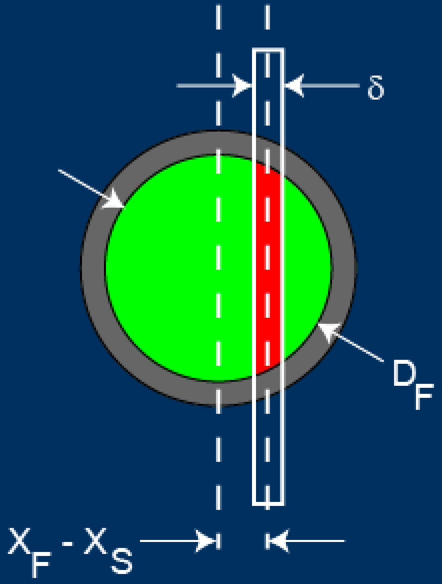
Optical Fibers

- Most convenient means to transfer signal from chamber to spectrograph
- Available with good transmission down to l ~193nm
- Subject to *drift* primarily from solarization in the UV
- And subject to *unit-to-unit* variation primarily from coupling geometry

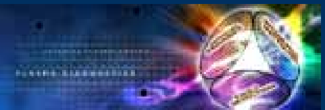
Fiber-to-Spectrograph Coupling

$$\text{Coupling} \approx I_0 \cdot \delta \cdot D_F \left[1 - \frac{2(X_F - X_S)^2}{D_F^2}\right] \cdot T(\lambda)$$

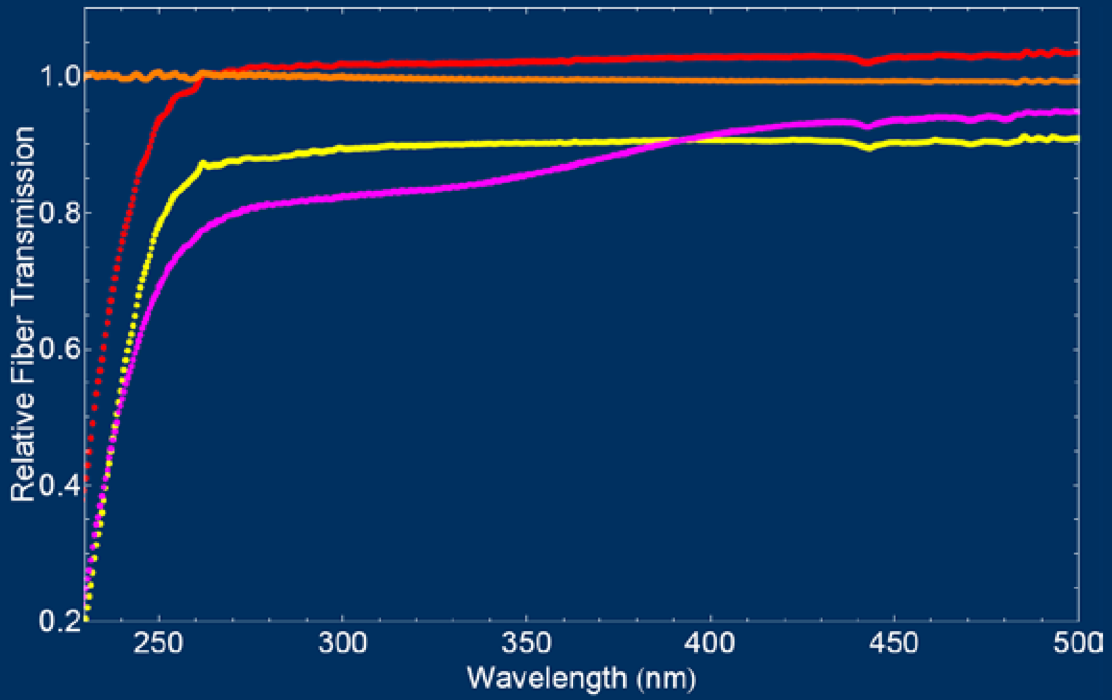
$$\begin{aligned} I_0 &= \text{Irradiance leaving fiber in W/cm}^2 \\ \delta &= \text{Slit width} \\ D_F &= \text{Fiber core diameter} \\ X_F - X_S &= \text{Transverse offset from fiber to slit} \\ T(\lambda) &= \text{Transmission of fiber} \end{aligned}$$



- Red overlap region is signal collected by spectrograph (“Coupling”)
- To lowest order coupling depends on transverse errors from slit to fiber core

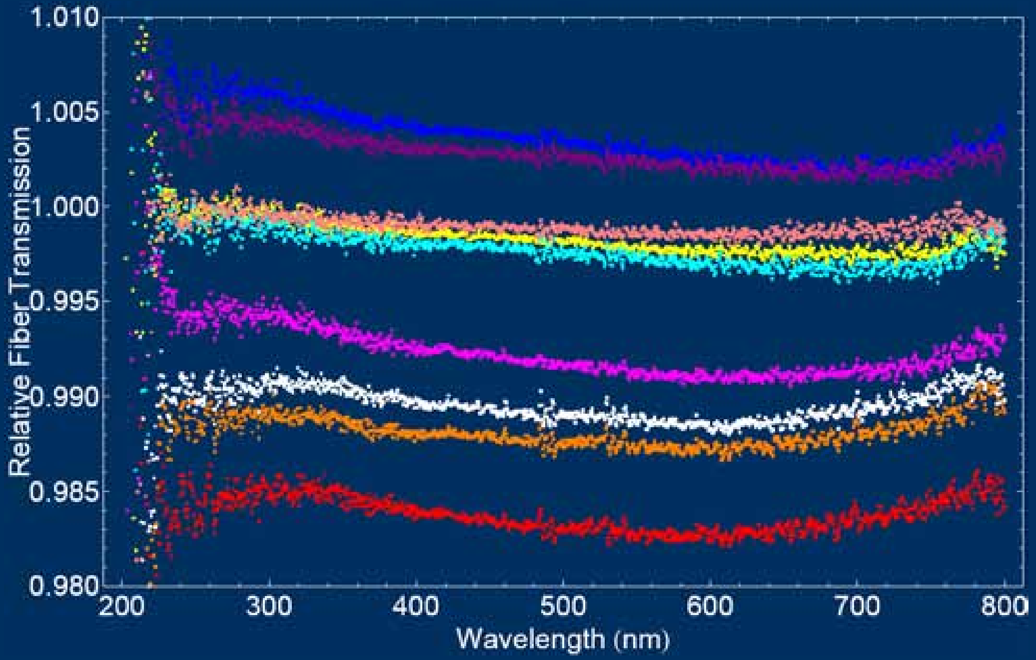


Variation Between Fibers



- Four different fibers measured relative to a (new) fifth
- D_F = 200mm, $X_F - X_S$ = ±0.002” à ≈13% variation *__unit-to-unit__*
- Solarization gives rise to up to 80% *__drift__* variation in deep UV

Repeatability of Single Fiber

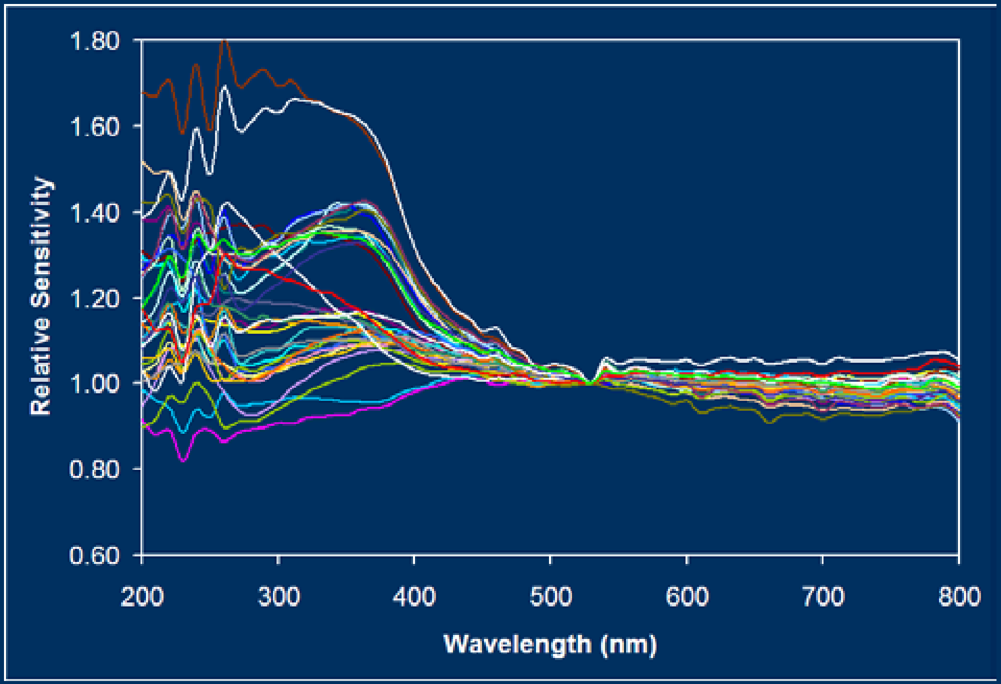


- Take one fiber and measure multiple repeat installations
- Mechanical connection variations and bend losses create unit-to-unit variation
- “Worst” case is ~5% (primarily due to bend losses), and careful control limits this to under 2% (as shown)

Xe Flashlamp

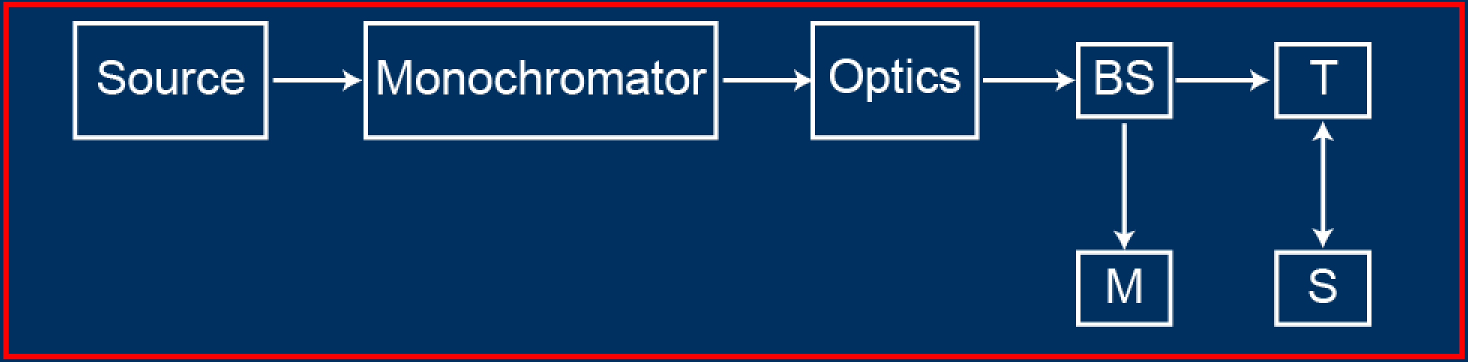
- Long-life (typically >1E9 shots), very broadband (190-2100nm) source
- *Unit-to-unit* variation
  - Overall intensity (easily accommodated with drive voltage)
- *Drift*
  - Decrease in intensity (again, adjust voltage)
- Generally very robust light sources for reflectometry applications

Spectrographs

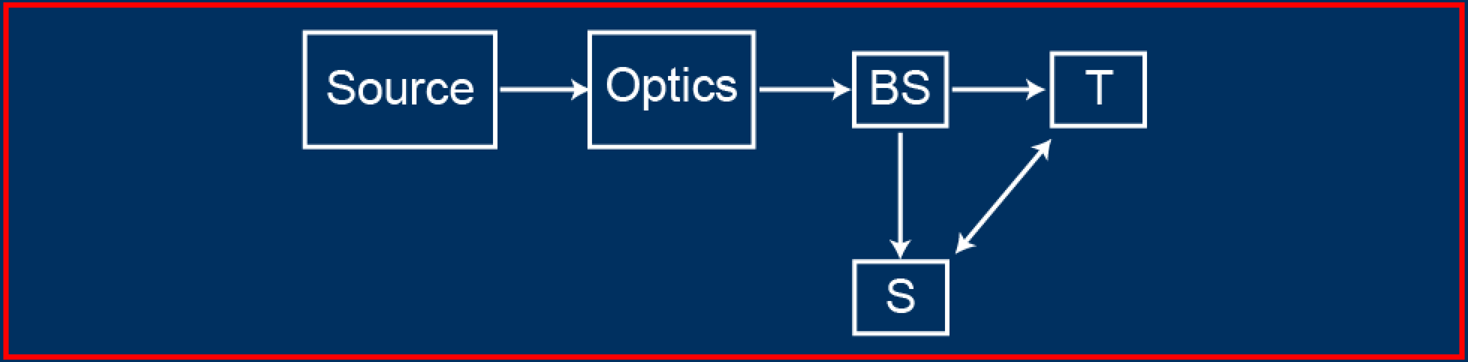


- *Unit-to-unit* variations
  - Calibration of I
  - Sensitivity calibration
- *Drift* sources
  - Temperature
  - Vibrations
  - Component creep
- Several design elements involved in minimizing these, but let's discuss sensitivity calibration

Adapted Substitution Method with Monitor



Original[5]

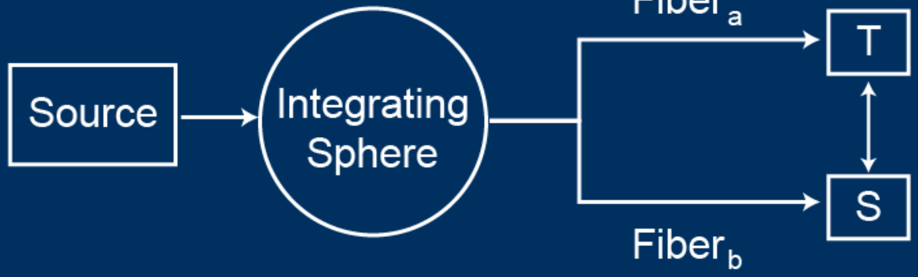


Adapted

- S & T are spectrographs, so can eliminate monochromator
- Standard can serve as monitor

[5] – *Larason, Bruce, and Parr, “Spectroradiometric Detector Measurements”, NIST Special Publication 250-41, 1998*

Implementation & Measurement Equation

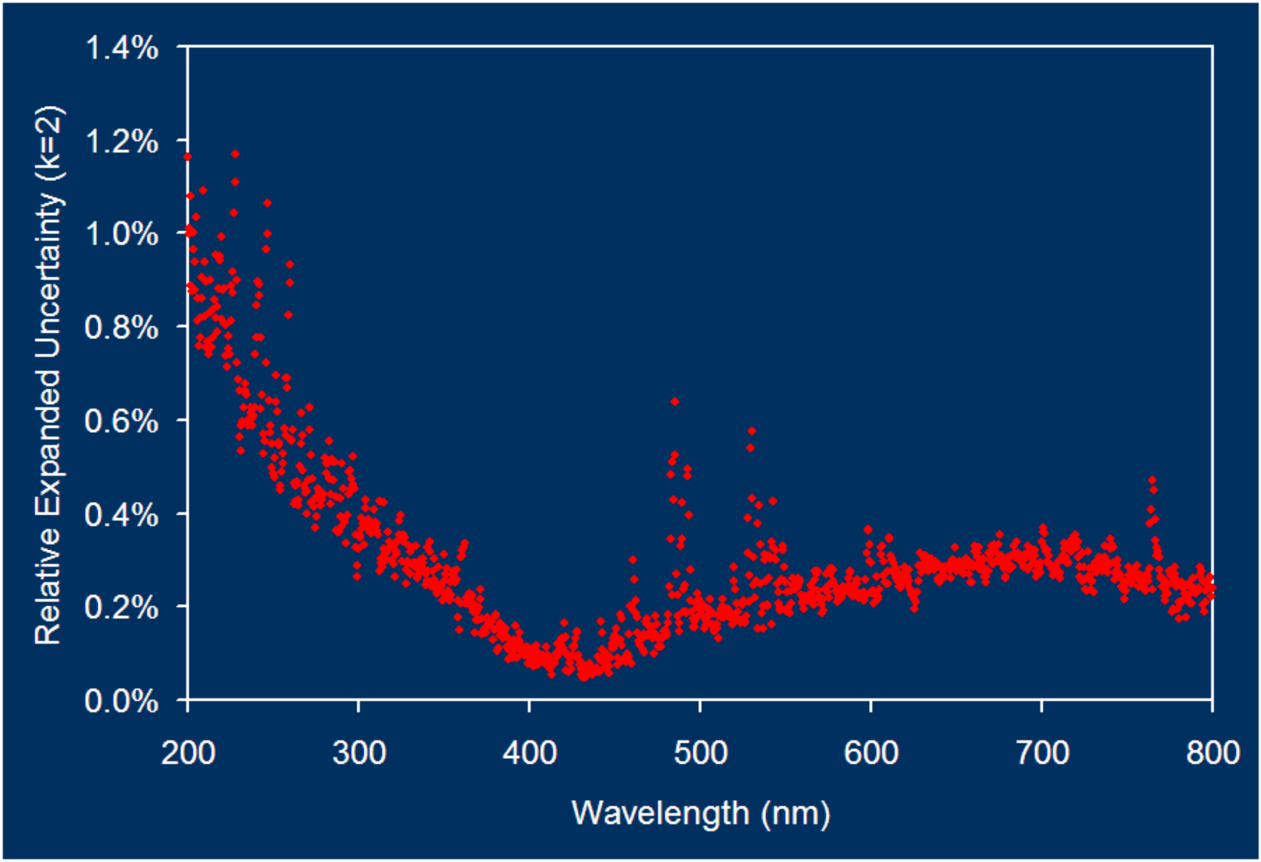


$$\begin{aligned}
V_T^{(1)} &= S_T \cdot \tau_a \cdot \Phi^{(1)} \\
V_S^{(1)} &= S_S \cdot \tau_b \cdot \Phi^{(1)} \\
V_T^{(2)} &= S_T \cdot \tau_b \cdot \Phi^{(2)} \\
V_S^{(2)} &= S_S \cdot \tau_a \cdot \Phi^{(2)}
\end{aligned}$$

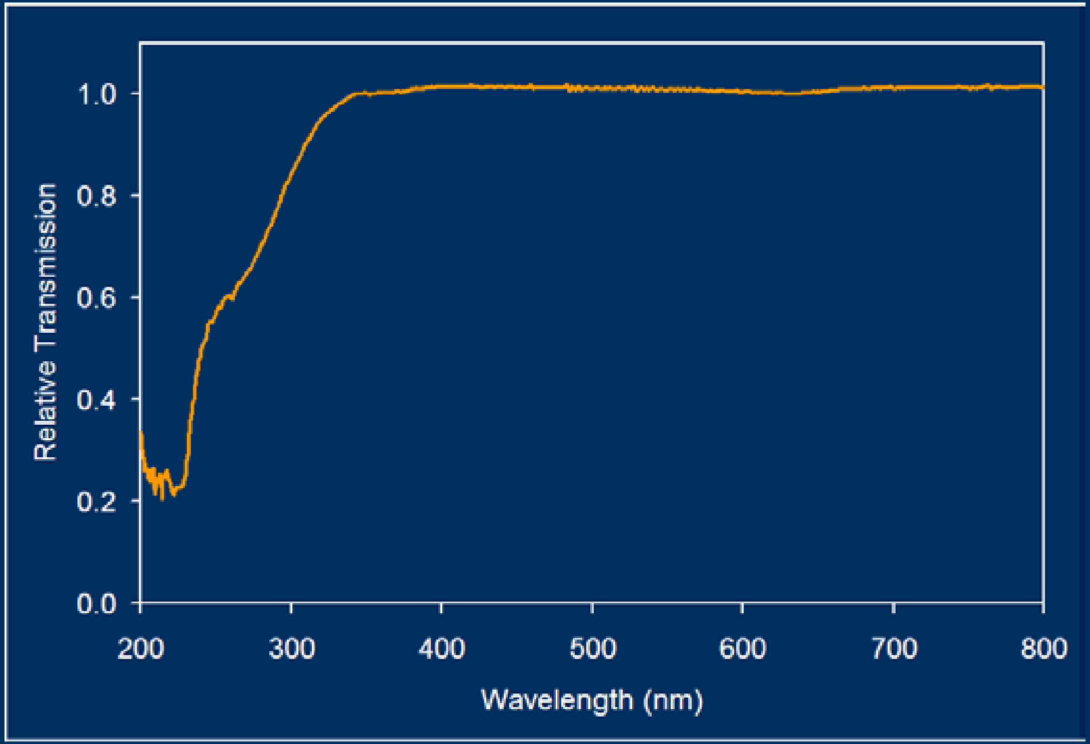
$$S_T = \sqrt{\frac{V_T^{(1)} \cdot V_T^{(2)}}{V_S^{(1)} \cdot V_S^{(2)}}} \times S_S$$

- Modification of standard measurement equation adapted for this approach
- Differential fiber to slit coupling contributes an overall offset (wavelength independent)
- Can use Xe flashlamp as source

Spectral Responsivity Measurement Uncertainty



Characterizing Fiber Transmission



$$\frac{\tau_a}{\tau_b} = \sqrt{\frac{V_T^{(1)} \cdot V_S^{(2)}}{V_S^{(1)} \cdot V_T^{(2)}}}$$

- Combining four measurements differently can give ratio of transmissions of two optical sub-systems
- Shown here as a method to characterize fiber solarization

Conclusion

- In semiconductor process control, integrated optical sensors play an important role in yield management and factory efficiency
- We have reviewed some of the sources of drift and variation in these sensors
- A broadband radiometric calibration process was described that allows low uncertainty and a convenient measurement method