UV Sources and Optics Applications, Infrastructure and Component Reliability

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Outline

- **Introduction**

- **UV Optics**
  - **Sources**
  - **Detectors**
  - **Bulk lens materials**
  - **Optical coatings**

- **Photocontamination control**
  - **Background information**
  - **Contamination mechanisms**
  - **Remediation**

- **Conclusions**

Background

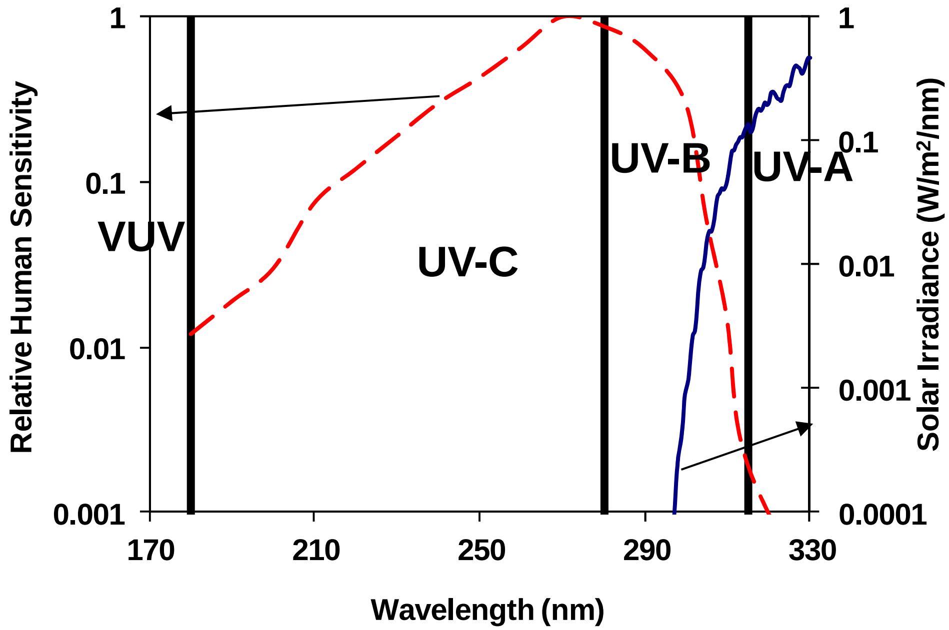
- The material for this presentation is mainly derived from
  - SPIE short course on “UV Optical materials” prepared by Vlad Liberman

  and
  - SPIE short course on “Contamination Control” prepared by Rod Kunz
- Both above courses were originally designed to address the technology of 193-nm and 248-nm based photolithography
- However, most of the presented material is relevant for any technology involving UV radiation and optical materials

Understanding Supplier Infrastructure

- UV optical systems require more stringent material selections
  - More limited than the visible range
- An educated user is in a better position to know what is available for the UV application space
  - Better choices can be made when initially acquiring a system
    - Sources, materials, coatings, detectors
    - System purge, material construction
  - Higher reliability performance from a more educated user

Ultraviolet Regions-- Nomenclature



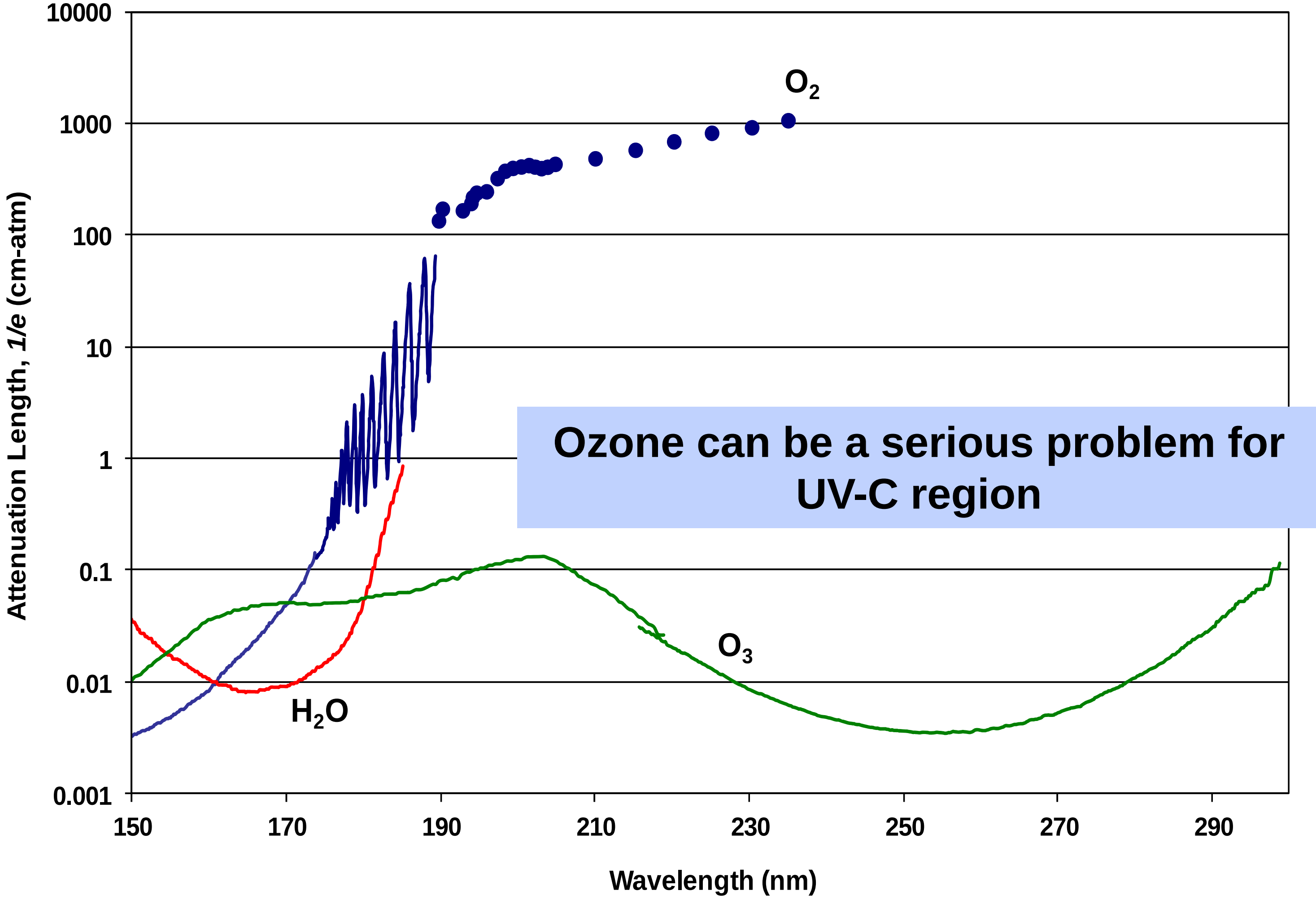
- **UV-A presents relatively few challenges for optical materials and contamination control**
  - **Issues become progressively challenging throughout UV-B and UV-C regions**
  - **NOTE: Solar Irradiance data from NREL**

    http://rredc.nrel.gov/solar/spectra/am1.5/ASTMG173/ASTMG173.html

Challenges Specific to Ultraviolet Region

- **Sources**
  - Lack of inexpensive UV solid state sources
- **Optical materials**
  - Initial bulk transmission requirements
  - Surface finish
    - Scatter increases at lower wavelengths
  - Radiation hardness
- **Metrology**
  - Lack of reliable materials properties
  - Few reference standards available
  - Lack of high precision metrology instruments
- **Contamination and ambient requirements**
  - Most common organics are absorptive in the deep UV range
  - Ambient purging necessary below in the deep UV range

Attenuation Lengths of Gaseous H_2O, O_2 and O_3



UV Light Sources – Overview

- **Gaseous discharge sources**
  - ***Example: Excimer lasers***
  - **PRO: High power and brightness**
  - **CON: Bulky and costly to maintain**
- **Solid state sources**
  - **PRO: Compact, easy to use, potentially low cost**
  - **However, still in development stages**
- **Note on units:**
  - **CW power measured in Watts**

    Cf. Total solar UV output is ≈ 10 W/m^2
  - **Pulsed energy measured in Joules**

    Cf. Total solar UV output is ≈ 1 J/m^2 every 100 ms

UV Laser Sources
Pulsed Gas Discharge

Excimer Laser

Wavel (nm)	Pulse Engy (mJ)	Spot Size (cm^2)	Rep Rate (Hz)
308 (XeCl), 222 (KrCl)	>100 mJ	Up to several cm^2	100- 1000
351(XeF), 248 (KrF), 193 (ArF)	>100 mJ	Up to several cm^2	100- 1000
157 (F_2)	10-30 mJ	Up to several cm^2	Up to 200

Nitrogen Laser

Wavel (nm)	Pulse Engy (mJ)	Spot Size (cm^2)	Rep Rate (Hz)
337	>100 mJ	Up to several cm^2	100- 1000

Excimer Laser

Benefits

- High pulse energy
- Large beam size

Drawbacks

- Poor spatial beam profile and pulse-to-pulse stability
  - Solutions exist but expensive
- High maintenance
  - Gas fills
  - Chamber optics

Applications

- Micromachining
- Microlithography
  - 248, 193 nm
- Laser eye surgery (193 nm)

UV Excimer Laser Applications

- Eye surgery

- Micromachining

- Photolithography

UV Laser Sources
Continuous Wave Gas Discharge

He-Cd

Wavel (nm)	Power (W)	Beam Diam. (mm)
325	10^{-2}	0.5

Ar^{+} Laser

Wavel (nm)	Power (W)	Beam Diam. (mm)	Method
351, 364	Up to 1	≈1	Fundamental
257, 244	Up to 1	≈1	SHG

– **Laser direct writing**
– **Micromachining**
– **Metrology**

UV Laser Sources
Solid State

IR-pumped, nonlinear conversion

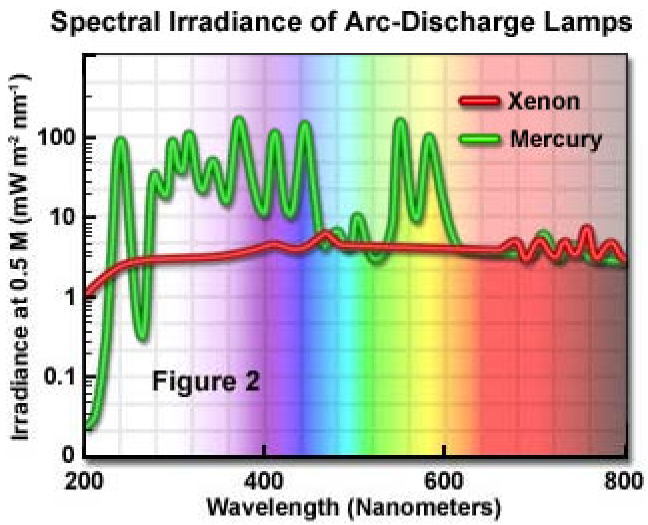
Wavel (nm)	Pulse Engy (mJ)	Spot Size (mm^2)	Rep Rate (Hz)
355, 266	2	1-2	>1000
213	0.5	1-2	>1000

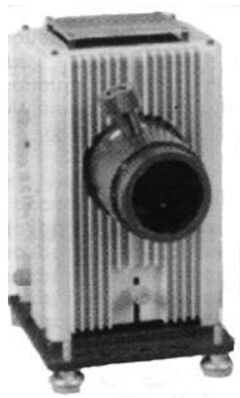
Tunable Sources: OPO Extensions

- For example, 355 nm pump, BBO crystal

Wavel. Range (nm)	Nominal Energy (mJ)	Technique
197-235	1-5	Tripling
203-300	5-30	Sum-frequency mixing with 355 nm

Discharge Lamp Sources for UV application

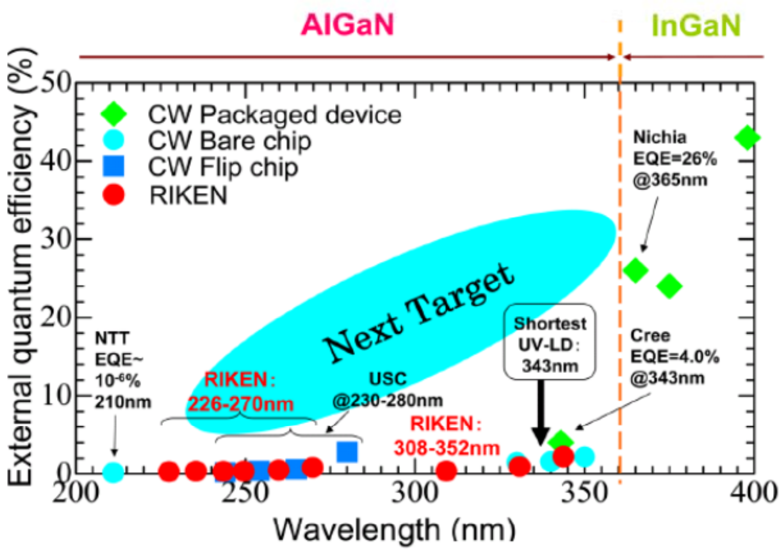




- **Incoherent irradiation– low brightness**
- **Uses**
  - **Metrology**
  - **Sterilization**
  - **Adhesive/sealant curing**

UV LEDs

- **Extremely attractive**
  - **Ultimate portability**
  - **Low cost**
- **Challenges**
  - **Material systems difficult to work with**
  - **Very low quantum efficiencies**
  - **Lifetime issues**
- **This is a subject of active research**
  - **Great interest in the defense and commercial user communities**



Hirayama et al. *Electron. Commun. Jpn* 93 (2010) 748.

Fig. 2. Recently reported external quantum efficiency (EQE) of nitride UV LEDs.

UV Light Detection

- Detector choice is determined by source type
  - Laser or lamp
  - Pulsed or CW
- And application requirements
  - Response speed
  - Dynamic range
  - Precision and/or accuracy
  - Durability

Common Detector Types and Their Primary Usage

Type	Application	Salient Features
Pyroelectric	Pulse energy or average power for pulsed lasers	Good dynamic range Spectrally flat Long term radiation durability
Photomultiplier tube	Low level light detection for metrology applications	Very high gain-photon counting possible
Photodiodes	Low level laser or lamp sources Array-based devices, such as dispersive spectrometers and beam profilers	High sensitivity Good dynamic range High detection speed
Thermopile	Average laser power, pulsed or CW	Long-term radiation durability Withstands high power levels Spectrally Flat Standards available

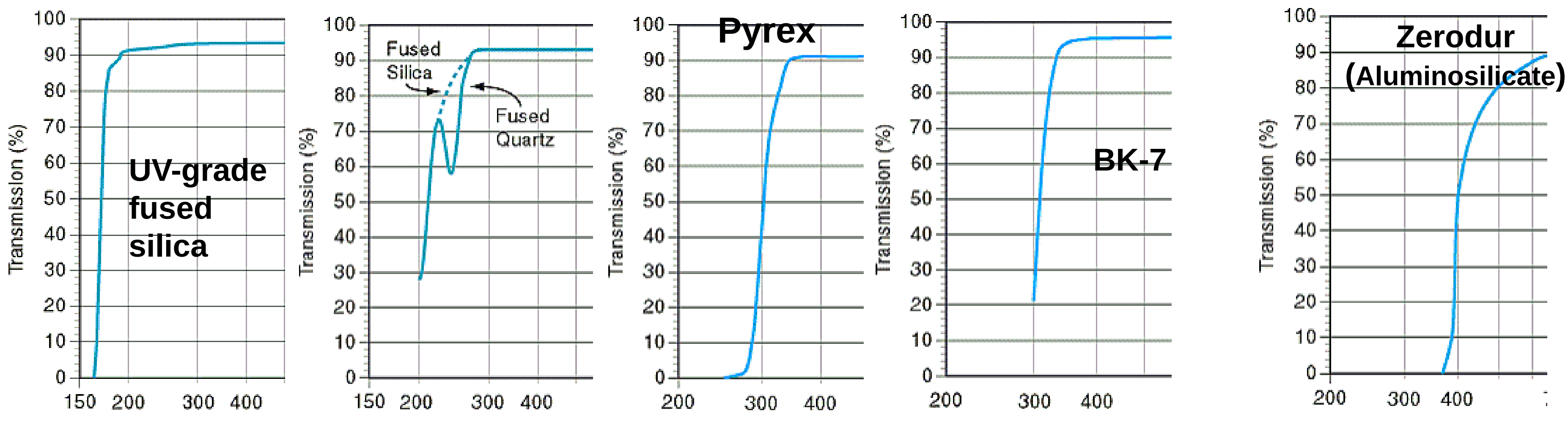
Bulk Materials for UV Optics

- **High purity fused silica**
  - Well-developed infrastructure
  - Cost and availability depends on purity
- **Fluoride crystals**
  - Needed for achromatic correction in optical designs
  - More expensive than fused silica
- **Some plastics may have limited use**

Common SiO_2 Window Material Transmission

(http://www.escoproducts.com)

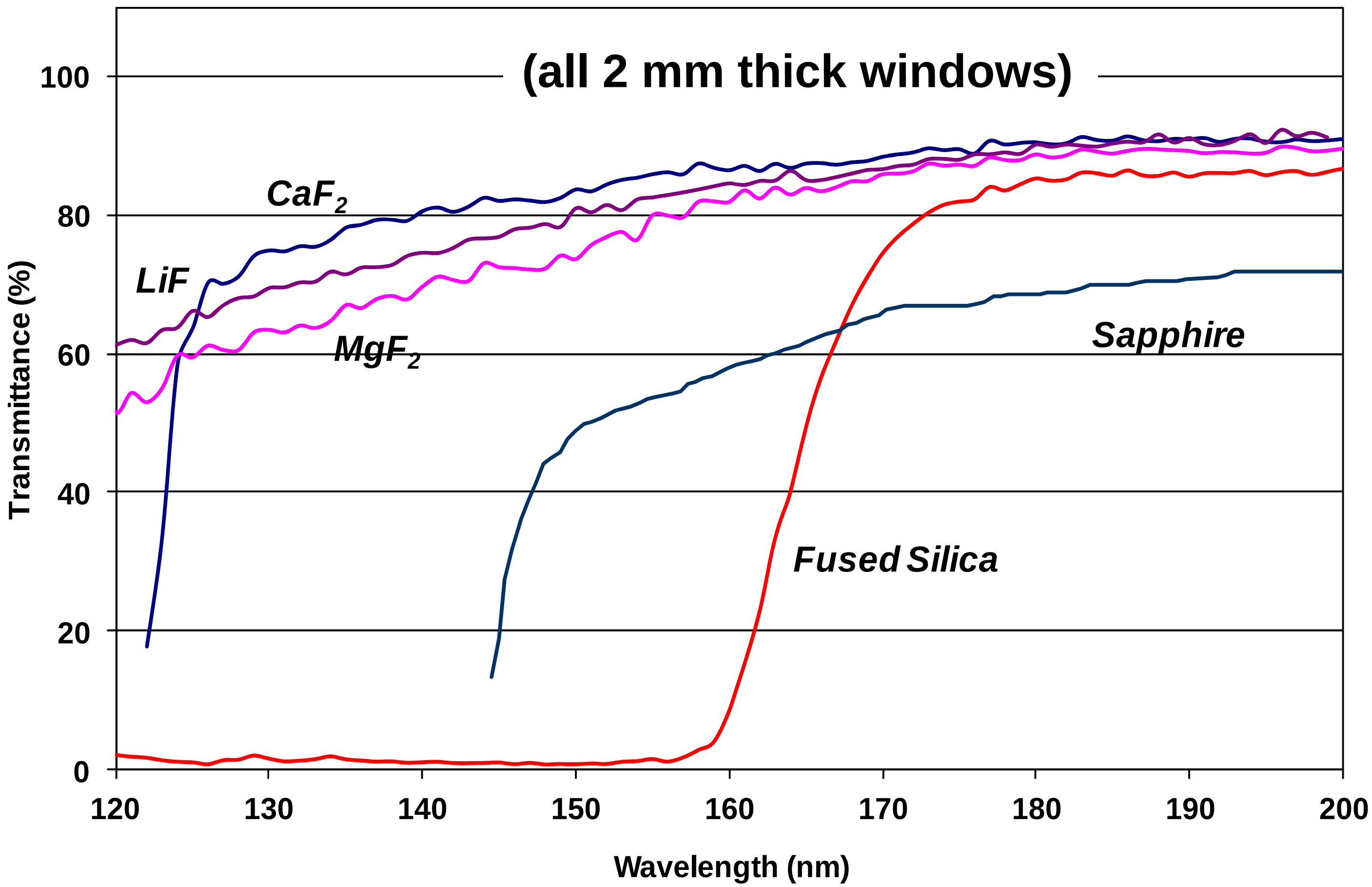
(all for 10 mm thickness)



Wavelength (nm)

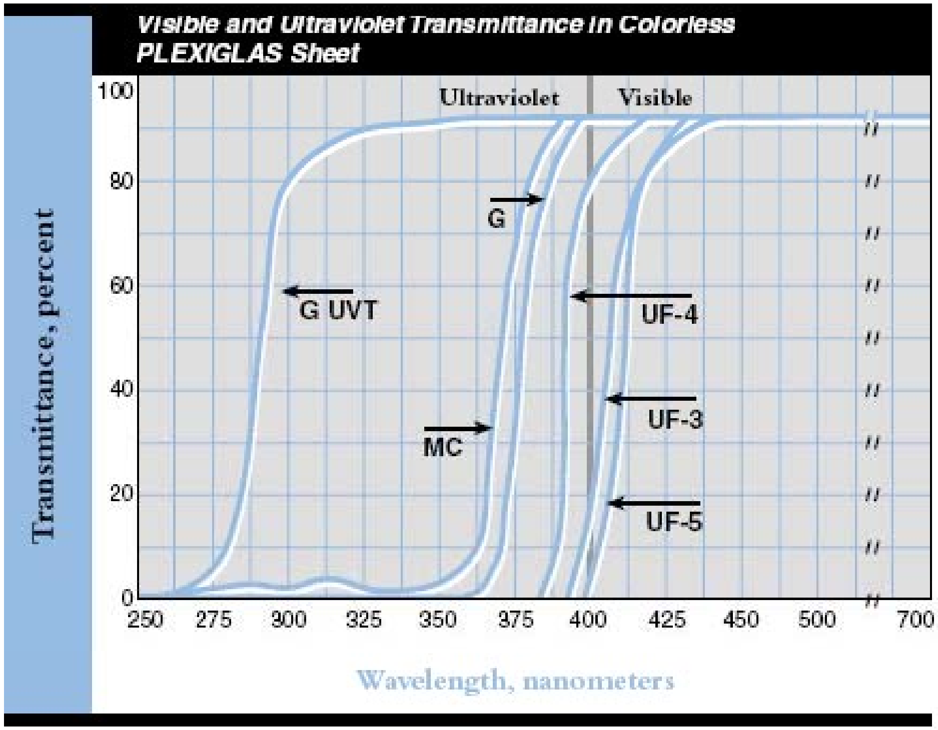
- Great variability in UV cutoff wavelengths for conventional glass windows
- Cost is a major factor when deciding to switch to high purity UV grade fused silica

Transmission of Optical Materials In the VUV Range



UV Transparent Plastics

Poly(methyl methacrylate) Transmission (Plexiglas™ or Lucite™) Typically, 1/8 inch thickness



http://www.plasticgenius.com/2011/05/infrared-and-ultraviolet-transmission.html

- **A number of polymers exhibit transparency in the UV**
  - **Polycarbonate**
  - **Teflon AF**
  - **PMMA**
- **However, most cannot be made into optical quality windows**
  - **Radiation durability is a major concern**

Common Types of Thin Film Coatings

- Antireflectance coatings
  - Throughput enhancement
  - Ghost image reduction
- Full reflectors
  - Laser windows
  - Turning mirrors
  - Retro-reflectors in imaging systems
- Partial reflectors
  - Beam delivery systems
  - Catadioptric imaging systems
    - Many custom designs
- Filters
  - Bandpass/high pass or low pass
  - Notch filters
  - Etc.

Materials Used for Coating Layers

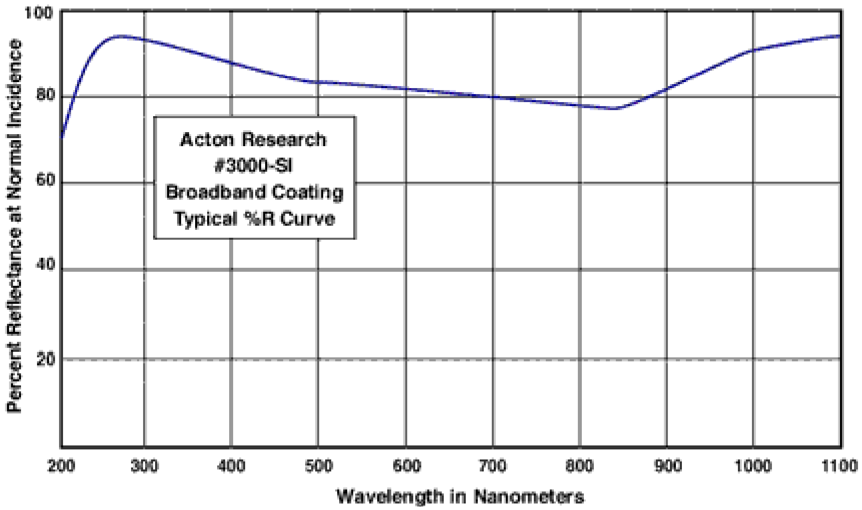
- Aluminum mirrors with dielectric overcoat
  - Broadband, >85% reflectance over the UV range
  - Inexpensive, simple to deposit
  - Durability under long-term laser irradiation inferior to dielectric-based mirrors due to higher absorption
- Dielectric designs
  - Based on constructive/destructive interference effects of incident and reflected light
  - Bandwidth usually a few nm for optimum operation
  - With appropriate layer material selection, absorption can be minimized
    - Excellent durability can be achieved
  - More complicated to deposit - higher cost
    - Optical film constants must be known
    - Endpoint monitoring for proper thickness
    - Optimization of deposition for denser defect-free films

Dielectric Coating Layer Materials for Ultraviolet Region

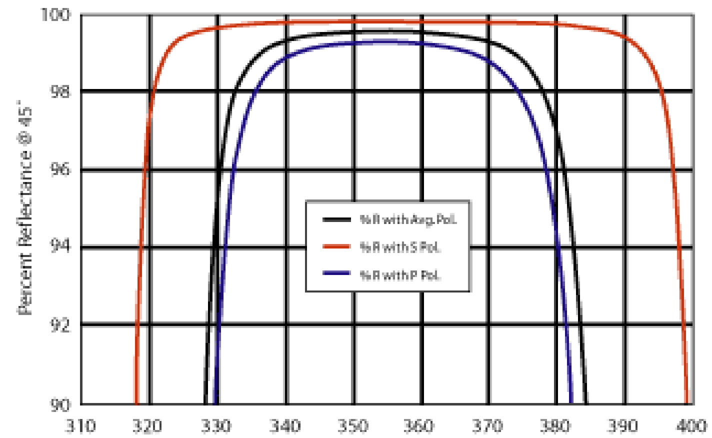
- Basic design involves alternating quarterwave layers of higher and lower index materials than the substrate
  - 3-5 layers for antireflectance designs
  - Up to 40 layers for high reflector applications
  - Layer thicknesses in the tens of nanometers, depending on wavelength and layer indices
- Fluoride or oxide materials may be used
  - High index
    - Fluorides: LaF_3, GdF_3, NdF_3
    - Oxides: Al_2O_3, HfO_2, ZrO_2
  - Low index
    - Fluorides: MgF_2, LiF, AlF_3
    - Oxides: SiO_2

Examples of Commercial UV Coatings

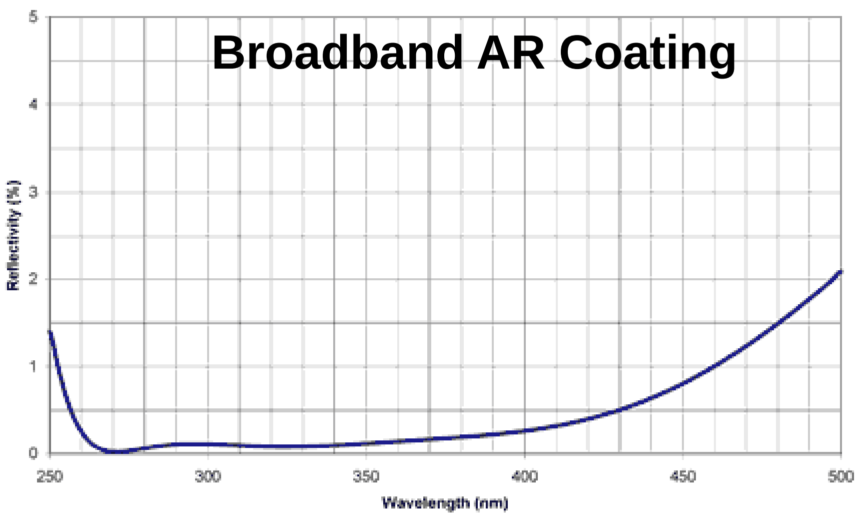
Broadband Full reflector



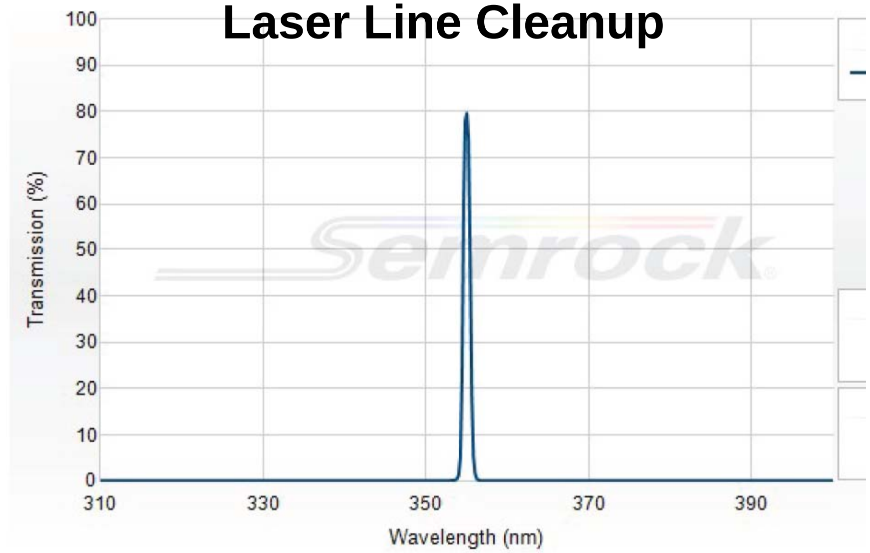
Narrowband Turning Mirror



Broadband AR Coating



Laser Line Cleanup



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“Switching Gears” – From Design to Durability

- What determines longevity of a UV-source-based optical system?
- Most common short term failures are not from fundamental material damage but from photoinduced contamination!
- How to separate contamination from material damage?
  - Contamination is strictly surface-limited, not bulk
  - Contamination will manifest itself as haze on the surface
    - As opposed to coating delamination
- It is best to consider contamination control during design stages
  - As opposed to implementing remediation strategies
  - Once the onset is observed, it may be too late to save the optical train from complete replacement!

Outline: Photocontamination Control

1. Description and background of photocontamination
2. Considerations prior to optical assembly
3. Contamination mechanisms
4. Dealing with contaminated optics
5. Monitoring for airborne contamination

(material for this section was kindly provided by R. Kunz, MIT Lincoln Laboratory)

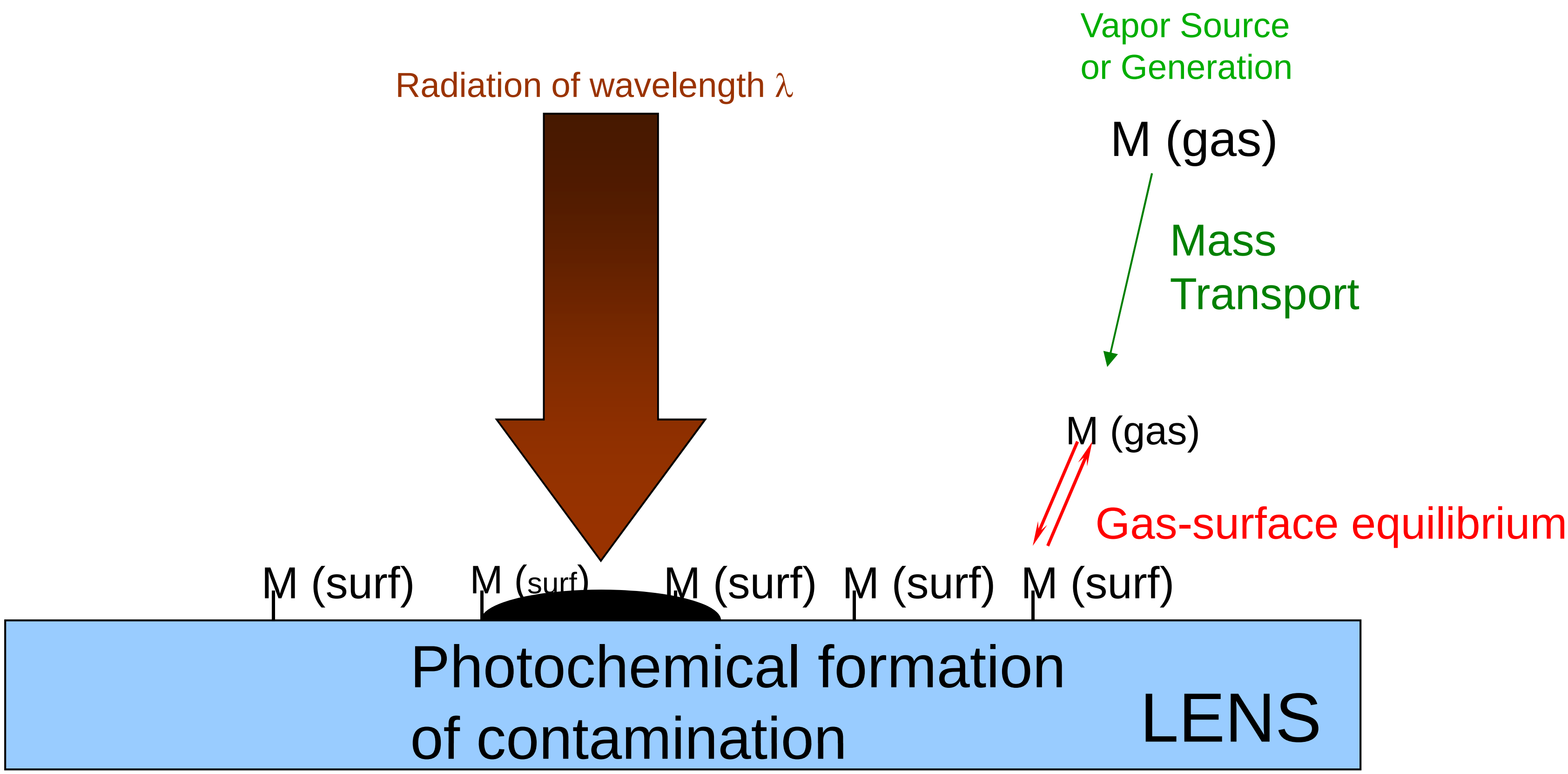
1. Overview of Photocontamination

- **Precision UV optics are being integrated into a wider range of applications**
  - **Lithography, metrology, interferometry, etc.**
  - **Operational requirement very demanding**
- **Short UV wavelengths interact with ambient in ways not experienced at longer wavelengths, leading to film formation on optical surfaces**
  - **Often referred to a “damage”, “solarization”, or “fogging”**
- **Phenomenon first experienced in space optics**
  - **Full-spectrum solar radiation, large thermal gradients in devices**
  - **Significant impact on early space missions**
  - **Large investment in infrastructure to manage problem**

Experience of the Space Optics Community

- **Best practices developed to mitigate problem**
  - **Defined acceptable levels and established measurement benchmarks**
  - **Contamination requirement as MIL-STD-1246C**
- **Database of acceptable materials established for use in this application**
  - **Standardization of tests for material acceptability**
- **UV Photocontamination specifications, as they pertain to semiconductor lithographic systems, may be even tighter than those for space optics**

Important Processes in Photocontamination



Afterwards: Identification, cleaning, and removal of the contaminant

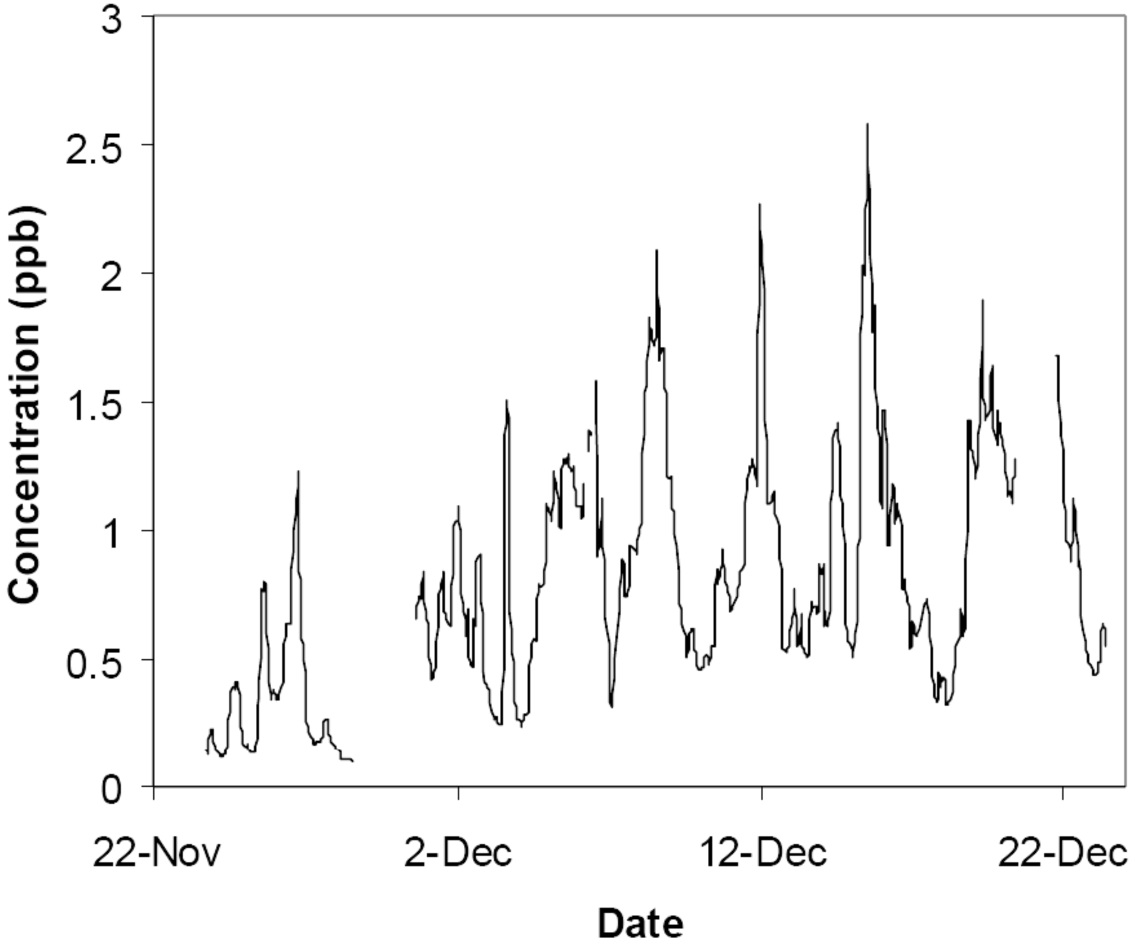
2. Considerations Prior to Optical Assembly

Its easier to build it right the first time than it is to remediate a poor design...
but the designer needs to understand the potential sources of contamination.

- **Operating environment**
- **Construction materials**
- **Stray light – the aggravating factor**

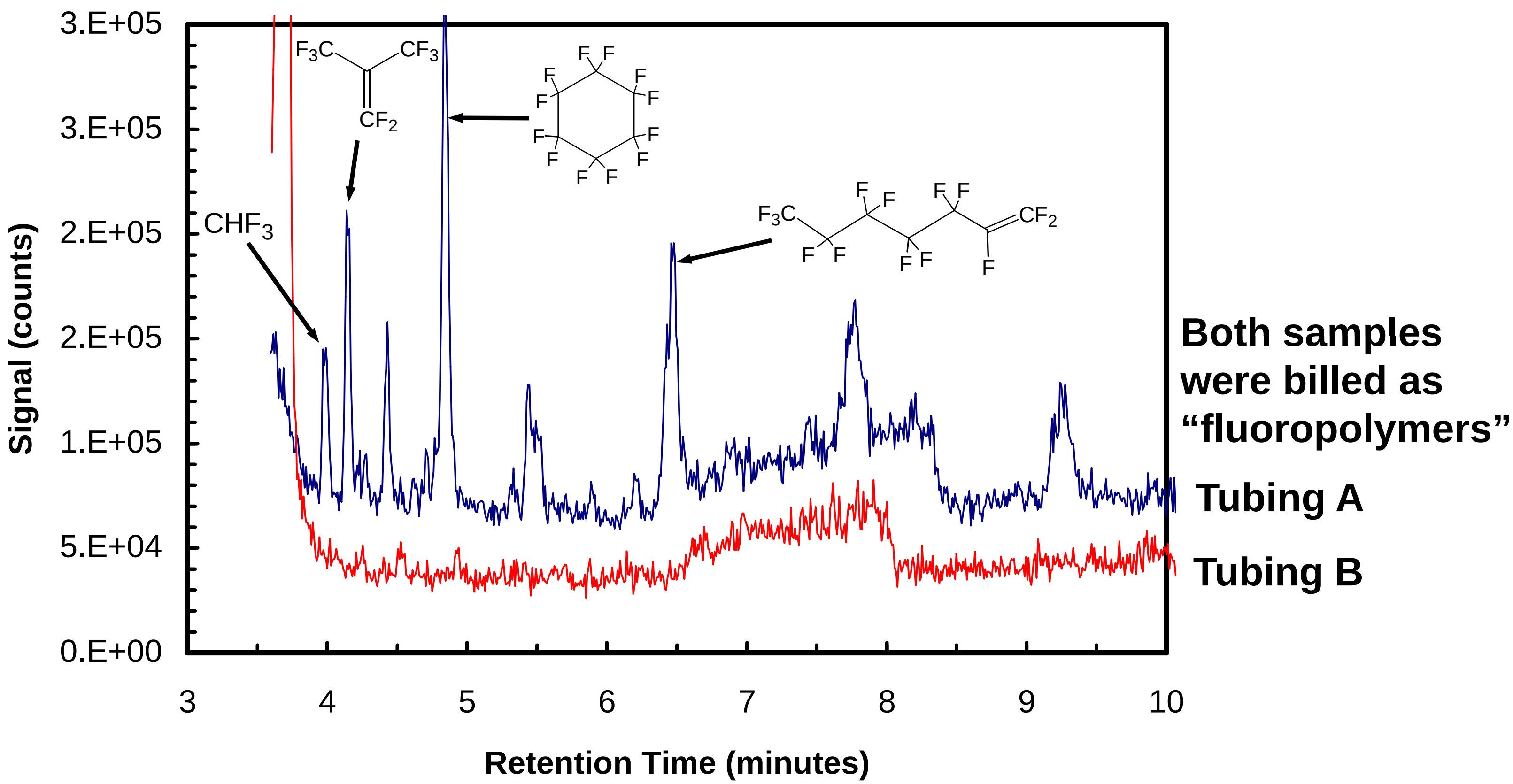
Time Variability in Ambient Gas Composition

Episodic contamination can be harder to quantify – Need real-time monitors



Gronheid et al., In-line monitoring of acid and base contaminants at low ppt-levels for 193nm lithography, Proc. SPIE Vol. 5754, p. 1591 (2005).

Example: Identification of “Contamination-Free” Flexible Purge-Gas Tubing



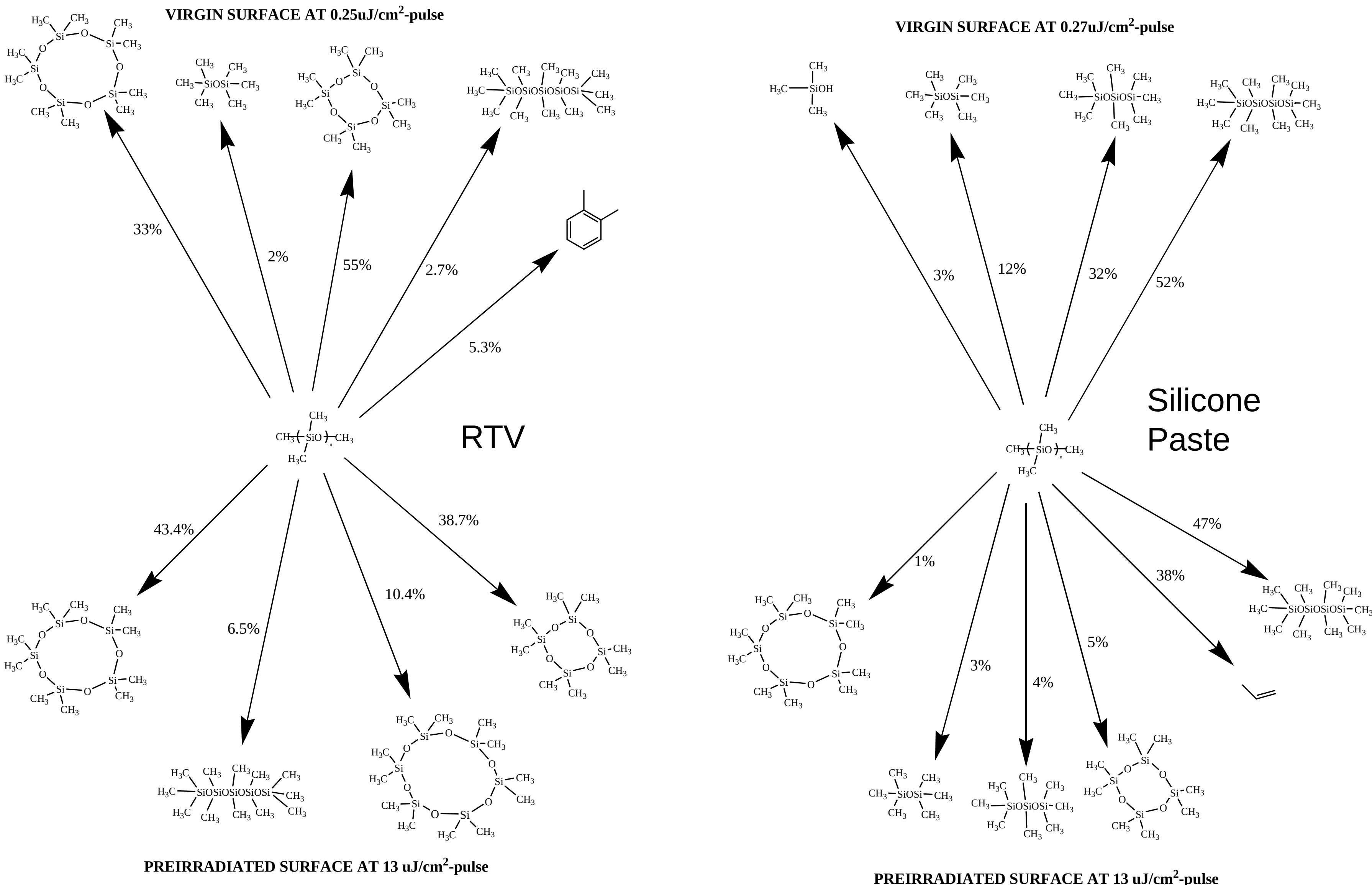
For 1-meter of tubing with 0.5-cm ID, nitrogen flowing at 1 liter per minute will be contaminated by:

- **11 ppb of various fluorocarbons for Tubing A**
- **<0.1 ppb total volatile organic compounds for Tubing B**

Potential Sources of Contamination

- Potting and/or encapsulation layers
- Adhesives
- Tapes
- Lubricants
- Sealants
- Photoresists
- Conformal coatings (paint, anodization, etc.)
- ..and just about anything else containing organic carbon

UV Degradation of Silicones



3. Contamination Mechanisms

- Origins of contaminating vapor and mechanisms of outgassing
- Mass transport to the lens
- Beam-induced chemistry – “photocontamination”
- Deposition models and the effect of wavelength
- Mechanisms and composition of deposits

Mass Transport to the Lens

- Airborne
  - Viscous gas flow (molecular flow such as that found in space and particle beam optics not possible)
  - Directed flow can increase or decrease contamination rate – it depends where the contaminating vapor is originating!
- Surface creep
  - Implicated in some types of oil-related contamination
  - Surface tension is the driving force
  - Distances can be surprisingly long (>cm)
- Surface diffusion
  - Not well understood, but rates can be high (>μm/sec)
  - Related to surface creep, but active at the molecular rather than bulk level

Outgassing Test Used in Space Industry: ASTM E 595

- **Material held at 125 °C for 24 hours**
  - **Comparison of initial and final sample weight yields the Total Mass Loss (TML)**
- **A cold plate at 25 °C is used to collect outgassing material**
  - **Amount of collected mass is the Collected Volatile Condensable Material (CVCM)**
- **Sample can then be placed in 50% humidity environment at 25 °C for 24 hours**
  - **Final weight yields Water Vapor Retained (WVR)**
- **Unlike space optics industry, no universal test exists for litho/UV Systems optics**

Outgassing Characteristics (An Example from NASA Database)

Material	TML% at 75 °C	TML% at 125 °C	CVCM (%)*
Adhesives			
R-2560	1.58	1.53	n/a
RTV-566	0.11	0.26	0.02
DC 93-500	0.07	0.08	0.05
Films			
Kapton FEP	n/a	0.25	0.01
Kapton H	n/a	1.17	0.00
Mylar	n/a	0.32	0.04
FEP Teflon	n/a	0.77	0.35
Oils and Greases			
Brayco 815Z	n/a	0.25	0.01
Braycote 803	n/a	0.24	0.13
Krytox 143AD	n/a	28.54	5.71
Vakote MLD73-91	0.40	n/a	n/a
Paints and Coatings			
S13G/LO	0.45	1.00	0.13
Chemglaze Z306	2.40	2.52	0.07
DC Q9-6313	0.40	0.39	n/a
Aremco 569	2.28	3.58	n/a
LMSC 1170	1.88	2.89	n/a

*Collected Volatile Condensable Materials

4. Dealing With Contaminated Optics

Identification, Mitigation, and Remediation

- Confirmation that contamination has occurred
  - Optical effects
  - Chemical identification
- Identification of the origin of the contaminating vapor
- Elimination of the source of the vapor
  - Removal
  - Shrouding
- Cleaning the optical surface
  - In situ methods if possible

- Silicone contamination cannot be cleaned– optics have to be replaced

Optical Effects of Contamination

- **Scattering**
  - **Leads to increased flare in litho tools**
    - **Many published methods to measure, track, and quantify**
    - **Tracking flare over time the single most useful diagnostic**
  - **Quantified ex situ via the Bidirectional Reflectance Distribution Function (BRDF)**
    - **Scattered intensity versus angle (off specular)**
  - **Severe contamination visible to naked eye**
    - **Scattering of visible wavelengths**
    - **Usually in pattern of lens exposure**
- **Absorption**
  - **Decreased system transmission**
  - **Increased or different thermal signatures**
  - **Increase in cross-field non-uniformity**
- **Periodic measurements of both BRDF/flare and transmission provides the earliest indication of contamination**

5. Airborne Contamination
What Needs To Be Detected?

- All compounds that can cause lens contamination
  - Siloxanes (<ppt)
  - Phosphonates (<ppb)
  - Hydrocarbons (>ppb)
  - Sulfur dioxide ("sulfate"), ammonia, other anions that can cause salt formation (nitrates, chloride)
- Time averaged values useful (~hours)
- Best if real time (~minutes)
  - Quantify concentration transients
  - Correlate with other activities - troubleshooting

Summary

- **There are a number of unique applications utilizing ultraviolet irradiation**
  - **Semiconductor processing**
  - **Medical**
  - **Micromachining**
- **These applications require a proper selection and understanding of UV sources and optical materials**
  - **Recent studies, stimulated by excimer laser-based UV lithography for semiconductor processing, helped to advance the understanding of this range**
- **Photocontamination of optics is a unique problem for the UV range**
  - **High photon energy causes bond breaking of most organics**
  - **Contamination needs to be well controlled to ensure long term reliability of optical systems**