Tecnologia a Plasma para o Processamento de Materiais

Diagnósticos em Plasmas

Diagnósticos Ópticos

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**Introduction**

**Plasma Diagnostics**

- Field of experimental techniques (broad area of technology) designed to provide information about the characteristics of a plasma.

- The data gathered can be used for a number of applications including:
  - improving basic understanding of discharge phenomena
  - validating discharge process models
  - documenting tool performance for fault detection
  - providing feedback signals for process control

- Depending on the desired information, there may be any number of better or worse techniques to provide that information. That makes the selection of the best diagnostic tools challenging.

The goal of this presentation is to provide you with a brief overview of the most common optical diagnostics techniques, discuss the merits and limitations inherent in the experimental methods.
Introduction

**Diagnostics vs Sensors**

- Both measurement methods, but with different connotations:
  - **Diagnostics:**
    - Large
    - Expensive
    - One-of-a-kind
    - Used in the laboratory on research devices
  - **Sensors:**
    - Simple
    - Small
    - Unobtrusive
    - Foolproof
    - Used in production

- Diagnostics for determining such quantities as \( n \), \( KTe \), \( Vs \), ... can be *remote* or *local*
Optical vs Electrical Diagnostic

- **Optical techniques:**
  - Rely on either the optical emission from the plasma or an external light source such as a lamp or laser to probe the plasma species.

- **Electrical techniques:**
  - Characterize properties of the plasma such as electron density, ion species or power input by measuring a current or potential change related to the plasma.

- In many cases, the optical measurements attempt to characterize a specific species since optical emission and absorption wavelengths are unique to a given atom or molecule.
Optical Diagnostic

Optical techniques generally exploit the optical emission from the plasma or probe the plasma species using an external light source such as a lamp or laser.

In general, the optical measurements attempt to characterize a specific species because optical emission and absorption wavelengths are unique to a given atom or molecule.

While optical emission signals are usually straightforward to acquire, useful correlations of the optical emission to a given plasma condition are difficult to obtain.
Optical Diagnostic Techniques

- Optical Emission Spectroscopy (OES)
- Laser-Induced Fluorescence (LIF)
- Optical Absorption Techniques (OAT)
- Thomson Scattering
- Negative Ion Photodetachment
- Optogalvanic Spectroscopy
- Laser Interferometry
- Full-Wafer Interferometry
- Microwave Interferometry
Optical Diagnostic - OES

Optical Emission

- Optical emission from a plasma occurs primarily through:
  - Electron impact excitation of atoms or molecules to an excited state, followed by a relaxation to a lower energy state
  - Release of a photon containing an energy equal to the difference between these two energy states
  - Analysis of photon energy (wavelength of light) and spectral emission information of species
  - Infer the composition of the species present in the plasma

- Plasma optical emission measurements can be grouped into two categories depending on the emitting species: atomic or molecular
Spectroscopy

- Measure the light emitted from a plasma as a function of wavelength, time and location
- Common remote optical diagnostic
  - The energy of the photons emitted is characteristic of the composition and energy state of species within the plasma
  - The spectra can be used to analyse both the chemical species that make up the plasma and their state of excitation
  - The large information content makes the interpretation of the spectra difficult
  - It is primarily used as a “fingerprint” that is compared with spectra taken while a process is working well to identify the state or drift of the plasma
- Non-intrusive
- Inexpensive
- Easily incorporated into an existing plasma reactor
- Popular in the microelectronics industry for monitoring the plasma processing

Optical Diagnostic - OES
**Optical Diagnostic - OES**

**Setting Up**

- Light from the plasma is conveyed through a window and a lens to entrance slit of spectrometer

- Alternatively, a fiber optic may be used to convey the light from the window to the spectrometer

- The diffraction grating and the concave mirrors in the spectrometer disperse the light and focus it onto the detector at the exit focal plane of the spectrometer

- The required components for setting up an optical emission spectroscopy include:
  - Optical window
  - Spectrometers
  - Detectors
  - Other optical components
By comparing the intensities of different spectral lines, one can determine not only the atomic species present but also the electron temperature, density and the ionization fraction.

- The relative intensities of two lines with different excitation thresholds can yield $K_T e$.
- The relative intensities of an ion line and a neutral line can be used to estimate the ionization fraction.
In plasma processing, the most useful and well developed technique is actinometry.

In this method, a known concentration of an impurity is introduced and the intensities of two neighboring spectral lines, one from the known gas and one from the sample, are compared.

Since both species are bombarded by the same electron distribution and the concentration of the actinometer is known, the density of the sample can be calculated.

\[ N_x = CN_a \frac{I_x}{I_a} \]
Optical Diagnostic - OES

Application: End-Point Detection

- Used to determine the end of a plasma etching process to better control etching fidelity

- Optical endpoint detection uses a change in the plasma-induced optical emission to determine when a process is finished

- End point detection in Cl₂ etching of ZrO₂
**Optical Diagnostic - OES**

**Advantages vs Disadvantages**

- **Advantages:**
  - Non-intrusive
  - Provides spatial and temporal resolution of the plasma emission spectra
  - Can be implemented on an existing apparatus with little or no modification
  - Can be used on more than one reactor
  - Relatively inexpensive

- **Disadvantages:**
  - Complex spectrum often difficult to interpret
    - Typically only the atomic lines are used in plasma process analysis
  - Difficult maintenance of the optical window
    - Deposition and/or etching of the window can significantly modify and attenuate the OES signal
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Laser-Induced Fluorescence (LIF)

- Technique where the emission is created by external light stimulation
  - The relaxation of the excited states yields photons of specific wavelengths used to identify various species in the plasma
- Used to monitor the density of species in a given energy level
- Non-invasive and local optical diagnostic
- The equipment is large, expensive and difficult to set up available in a relatively few laboratories
- Capable to make spatially resolved measurements
- Only way to measure Ti without using a large energy analyzer
**Optical Diagnostic - LIF**

**Background**

- Pump up the ground level to an excited state by one or more photons
- Detect enhanced emission from upper level at another wavelength
- Very good spatial resolution and detectivity

\[ I_{2\rightarrow3} = C N_1 I_p e^{-t/\Gamma} \]

- LIF is directly proportional to the ground state density
Optical Diagnostic - LIF

Data Work Out

- Integrated intensity: $n(r,z)$
- Doppler width: $T(r,z)$
- Doppler shift $\nu - \nu_0$: $\nu(r,z)$
- Velocity distribution $f_\nu(r,z)$
- LIF lifetime vary depending on the plasma electron density and/or spatial location
Two-Photon LIF

Advantages:
- no demanding VUV-generation
- non-resonant fluorescence detection possible
- self-absorption can be avoided

Disadvantages:
- low 2-photon cross sections require high laser intensities
- 2-photon cross sections often not known

Use of multiphoton LIF is limited to a few special cases
Molecular LIF

- One photon is used to excite a ground state molecular level to an excited electronic manifold of states

- Large number of ground states within the electronic / vibrational / rotational manifold

  
  spectra can be very complex

- Analysis of the molecular LIF spectra outcomes:
  - relative density of the ground state
  - rotational and vibrational temperatures
Advantages vs Disadvantages

Advantages:

- Sensitive
- Extra info from time behaviour
- Experimentally straightforward

Disadvantages:

- Not quantitative
- Depending on medium conditions (quenching)
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Optical Diagnostic

Optical Absorption Techniques

- Used to measure the absolute, line-integrated density of a species
- Powerful method to characterize the density of a species in the plasma

Absorption spectrum of CO2 around $\lambda = 15.34 \, \mu m$

Requirements:
- Two access points across the measurement area
- Large enough density of the species to give a detectable signal
Optical Diagnostic - OAT

Background

A. Simple absorption setup

Intensity of a transmitted signal, \( I/I_0 = \exp(-\sigma_{ab} N_1 d) \)

Absorption cross section (atomic absorption):
\[
\sigma_{ab}(\nu) = A_{21} \left( \frac{\lambda^2}{8\pi} \right) (g_2/g_1) g(\nu)
\]

Lineshape function:
\[
g(\nu) = (4 \ln 2/\pi)^{1/2} (1/\Delta \nu_d) \exp \left\{ -4 \ln 2 \left[ (\nu - \nu_0)/\Delta \nu_d \right]^2 \right\}
\]

Doppler linewidth:
\[
\Delta \nu_d = \left( 8kT \ln 2/Mc^2 \right)^{1/2} \nu_0
\]

- Light sources (atomic absorption):
  - Laser
    - Narrow linewidth
    - Density, velocity and temperature
    - Expensive
  - Lamp
    - Atomic emission
    - Density
    - Low cost
Self Absorption

- Uses the plasmas’ own optical emission to probe its absorption

B. Optical self absorption

- Complicated derivation of an absolute line-integrated number density:
  - Unknown emission and absorption lineshapes
  - Combination of plasma light and transmission in the measured signal

- Requires a minimum amount of hardware
  - Ideal for determination of relative changes
Light Diagnostic - OAT

**Molecular Absorption**

- Large number of possible states
- Molecular cross sections smaller
- Large number of molecules
- Absorption cross section data not as well developed
- Molecular absorption spectra complex
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**Optical Diagnostic**

**Thomson Scattering**

- Elastic scattering of photons at free electrons
  - Rayleigh scattering is the same, but then at electrons which are bound in an atom

- Electron may change velocity: Doppler shift of the scattered photon

- Used to measure the electron density and the electron energy distribution function or temperature without putting a probe in the plasma

- Non-intrusive
- Difficult but possible in lamps
Optical Diagnostic - Thomson Scattering

Background

- Scattering of photons on free electrons in a plasma

- Scattered intensity

- Doppler broadening
Optical Diagnostic - Thomson Scattering

Advantages vs Disadvantages

- Very small electron/photon scattering cross section
- Need to reduce scattered laser light many orders of magnitude

Applications of Thomson scattering techniques are challenging

- Advantages:
  - reasonable agreement between measurements of the electron energy distribution function using probes and scattering
- Disadvantages:
  - signal averaging is critical
  - the possibility of photochemistry change local plasma environment

Measurements have typically been performed in argon to investigate fundamental discharge physics
Conclusions

There are several optical diagnostic techniques:

- OES:
  - Density, temperature, ionization fraction
  - Inexpensive
  - Simple to set-up
  - Monitoring

- LIF:
  - Density, temperature, velocity
  - Sensitive
  - Large, expensive
  - Difficult to set-up

- OAT:
  - Absolute density
  - Not very expensive
  - Not very difficult to set-up

- Thomson Scattering:
  - Density, temperature
  - Difficult to obtain data
  - Investigation of fundamental discharges

Applications are challenging

- We must know them to choose the best one for our proposal
References


- G. M. W. Kroesen, *Laser Based Diagnostics*, Eindhoven University of Technology

Do not use a optical diagnostic unless you have read these references... and much more
Introduction

Remote vs Local Diagnostics

- **Remote:**
  - Do not require insertion of an object into the plasma
  - Do require at least one window for access
  - Depend on some sort of radiation
  - The window as to be made of a material that is transparent to the wavelength being used

- **Local:**
  - Measure the plasma properties at one point in the plasma by insertion of a probe
  - Probes have to withstand bombardment by the plasma particles and the resulting coating or heating
  - They have to be small enough so as not to change the properties being measured
Optical Diagnostic - OES
Atomic Emission

- Only electronic state transitions can occur
  - Reasonably straightforward

- Discrete lines characteristic of the atomic energy levels

Atomic spectra peaks:
- Sharp
- Nearly monoenergetic
- Well-defined
Molecular Emission

- Molecules have a large number of electronic states and also have both vibrational and rotational states.
- Small energy differences between the vibrational and rotational states.
- Broadening of emission energies caused by collisions.
- Movement of the emitting molecules.
- The emission overlaps and forms bands rather than sharp emission peaks at easily identified frequencies.
- Molecular emission spectra are generally more complicated than atomic line spectra.

- Electronic transitions: 10 000 – 100 000 cm⁻¹ (near IR to vacuum ultraviolet)
- Vibrational spacings: 100 – 1000 cm⁻¹ (near IR to far IR)
- Rotational spacings: 0.5 - 5 cm⁻¹ (microwave region)
Optical Diagnostic - OES

Setting Up – Optical Window

- Quartz or sapphire is used to maximize the transmission of short wavelengths of light

- Experimental difficulties:
  - Deposition on the chamber window through which the optical emission is sampled
  - Deposits can selectively absorb emission, altering the spectra that are observed

- Overcome:
  - Purging the window with the input gas to keep the window clean
  - Heating of the optical windows could also reduce the deposition
Optical Diagnostic - OES

Setting Up – Spectrometers

- Most of the photon detectors have a fairly flat response for different wavelength of the photon.

- It is essential to disperse the plasma emission into the different wavelengths prior to the photo-detector.

- Most commonly used spectrometers:
  - Prism:
    - Works because refractive index of glass depends on the wavelength.
    - Its use is not as common these days due to its limited resolving power.
  - Gratings:
    - A resolving power of 100 000 can be easily obtained in a moderated size grating.
    - Diffraction gratings have been used extensively for OES.
  - Filters:
    - A high quality filter can provide about 1-2 nm resolution.
    - Main advantages: low cost and high optical throughput (~80% of light transmission).
Optical Diagnostic - OES

Setting Up – Detectors

- Photodetectors are essential for collecting the optical emission for the subsequent analysis

- The detector can be a photodiode, a photomultiplier or an optical multichannel analyzer (OMA)

  - Photomultiplier
    - can see only one part of the spectrum at a time
    - the most sensitive detector for faint signals
    - higher resolution spectra
    - cheaper
    - most frequently used

  - Photodiode:
    - used to isolate a particular spectral line (with interference filters)

  - OMA:
    - records an entire range of wavelengths on a CCD
    - for scans of a single line
    - for recording an entire spectrum

  collects data much more rapidly
Molecular Absorption

- Large number of absorption lines
- Important to know the laser frequency accurately

Simultaneously recording:

- absorption signals of a known gas
- provides absolute frequency reference points
- transmission signals from an etalon
- provides a relative frequency offset

Low absorption cross sections in the IR:
  - techniques based upon modulation and derivative spectroscopy
  - multipass cells