Optical properties of tantalum oxide films produced by high density plasma enhanced chemical vapor deposition

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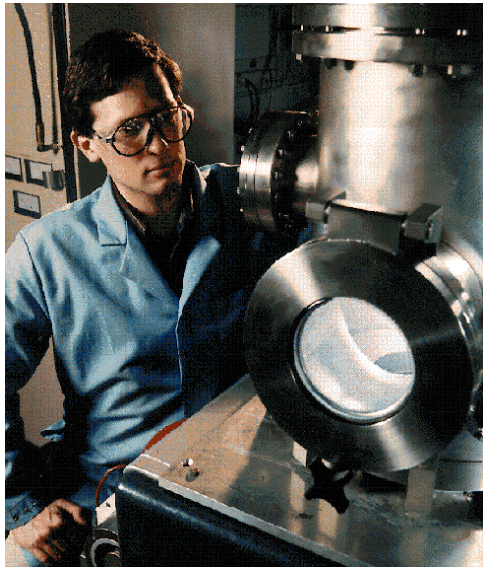
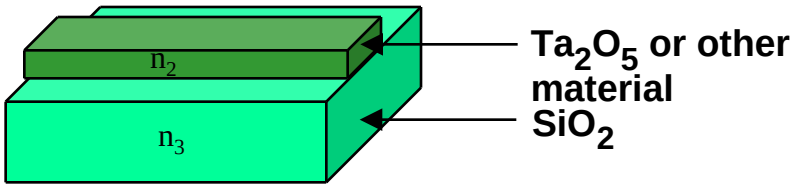
Agenda

- Motivation: develop waveguide materials for on-chip optical interconnect applications
- Inductively coupled high density plasma source description
- Gas phase diagnostics using optical emission spectrometer and mass spectrometer
- Results
  - Refractive index and bandgap vs deposition conditions: n >2.1, BG>4.2
  - Deposition rates of up to 250 A/min
  - Good stoichiometry
  - Low impurity content
  - Dielectric constant around 29
- Summary

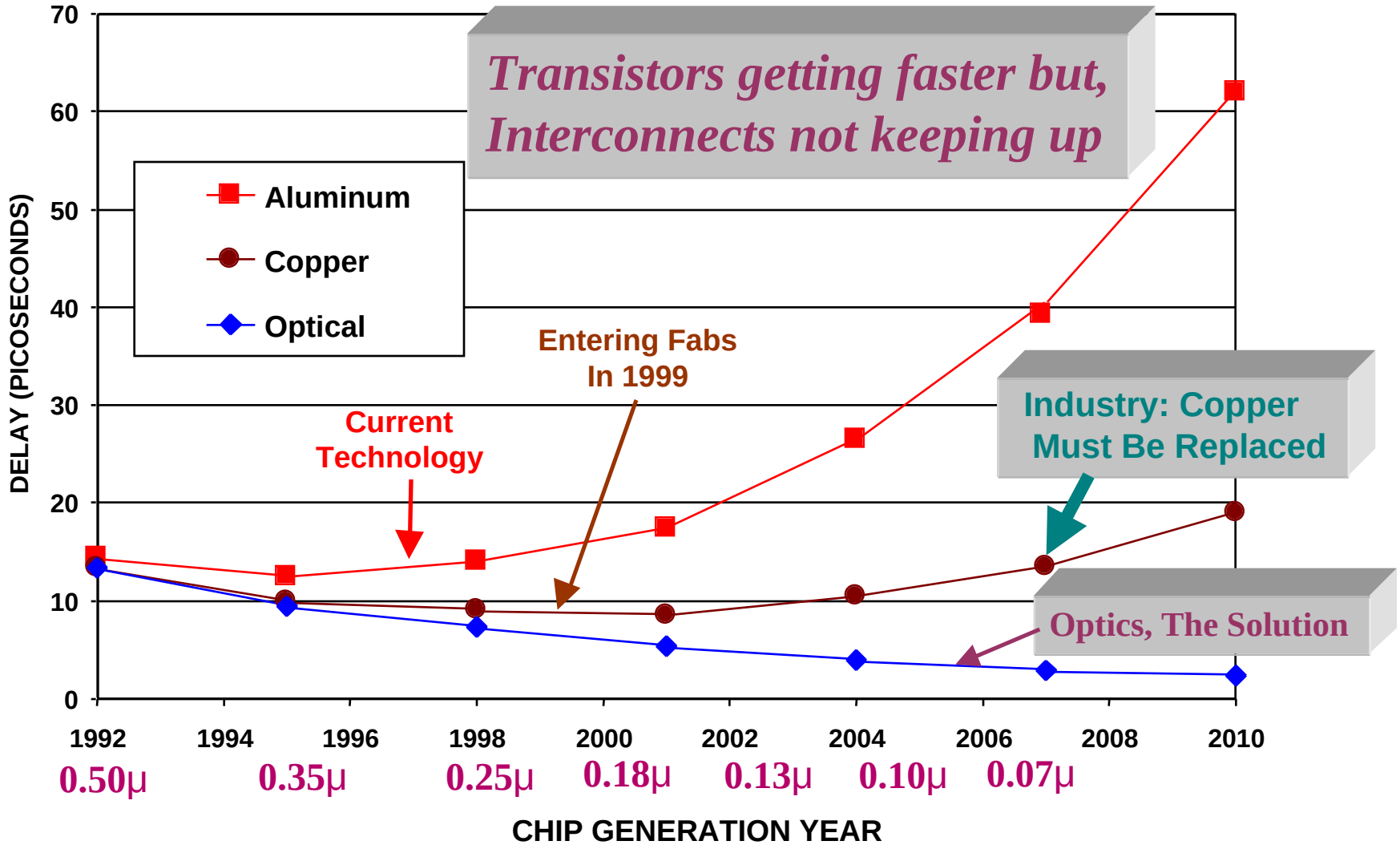


We are Addressing the Science Issues Related to Advanced Optical Interconnect (OI)Technology

- Chip interconnect is the limiting factor in electronic device timing and process complexity today
- No identified long-term solutions beyond copper/low-k materials - 2007 (SIA roadmap 1997)
- New integrated nano-optical sources, waveguides, detectors, and devices are needed (200 nm scale and smaller): on-chip
- ORNL's capabilities in materials, electronics, and optics are used
  - Hosted optical interconnect workshop for high performance computing next month (November 8,9, 1999) (http://www.ornl.gov/optical)
- Desired waveguide material properties:
  - High refractive index: >2 (high contrast with oxide)
  - High band gap: >4 (0.5 to 1 eV higher than blue light emitters)
  - Potential materials: silicon nitride, tantalum oxide, hafnium oxide

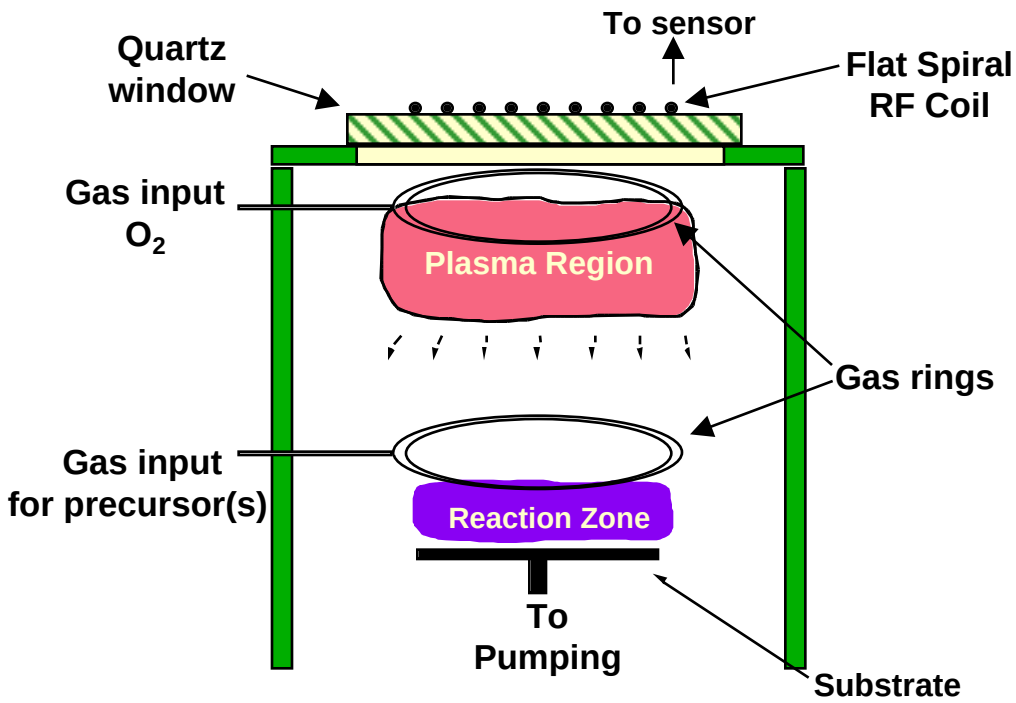


Optical Interconnect Is A Viable Solution Beyond Copper

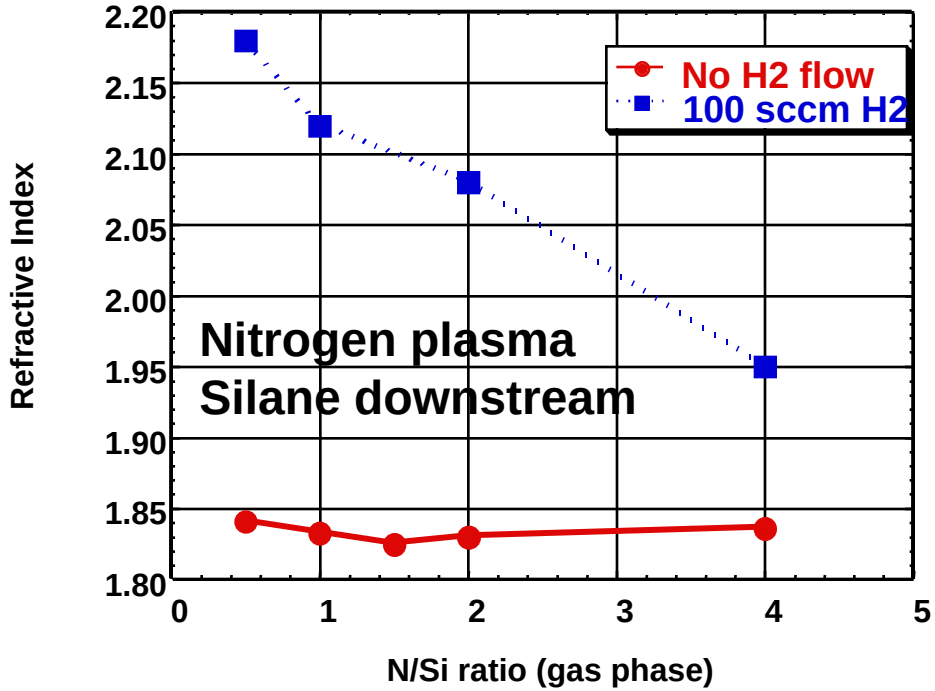


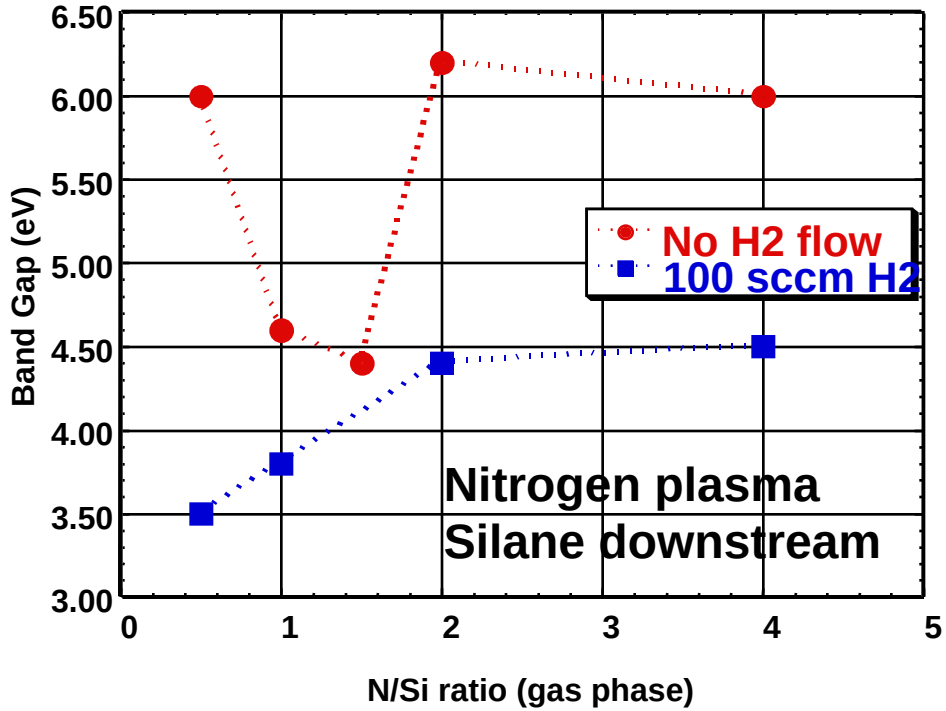
Our approach uses an inductively coupled plasma to produce reactive species to drive process improvements

- Atomic species produced in high density plasma region
- High efficiency for dissociation of oxygen
- Plasma density and ion energy are decoupled
- Tantalum precursor is injected from a heated gas ring downstream (argon carrier gas)
- Evidence for high flux of atomic species bombarding the surface during film growth
- Sensor at coil input used to determine power coupling



SiN results from last year showed importance of atomic species production

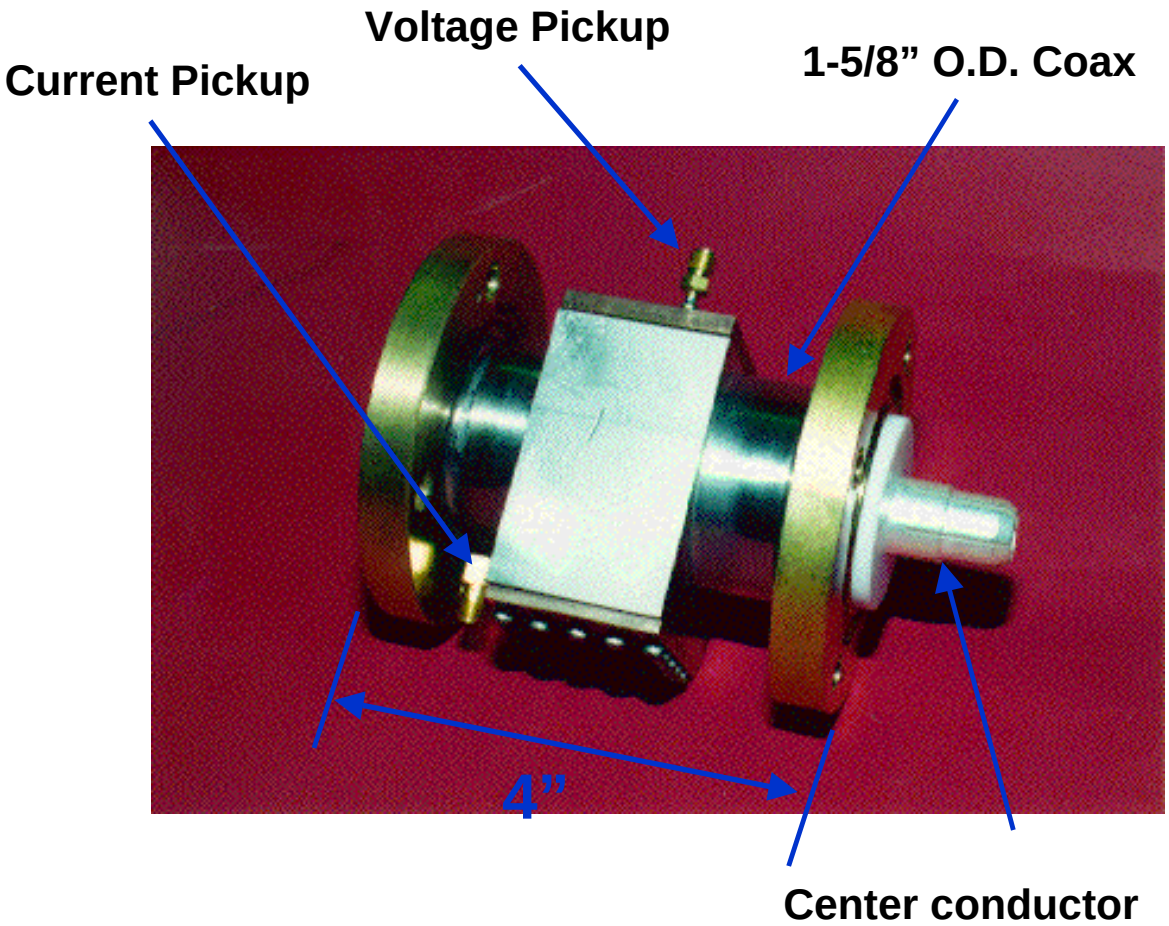




- With the addition of hydrogen in the ionization region, the processing window substantially increases (atomic hydrogen production is playing a role): Refractive indices > 2.0 are possible
- With hydrogen addition, the bandgap increases with nitrogen gas flow
- The goal of a band gap > 4.0 eV with a refractive index > 2.0 can be achieved by the addition of hydrogen in the gas phase

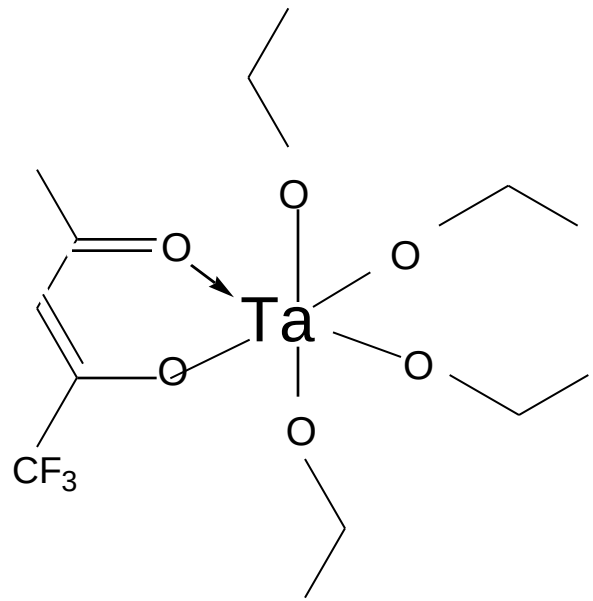
Efficiency and loading are measured with a high power sensor

- Capable of handling several 10's of kW of reactive power
- Current pickup via Faraday shield in outer conductor of coaxial line
- Voltage pickup via small disc capacitively coupled to center conductor
- Machined from a solid piece of stainless steel and nickel plated to give a through impedance of 50 ohms
- Calibrated by terminating into a 50 ohm load and using network analyzer and calorimeter load



Sensor located at input of coil

Tantalum Precursor

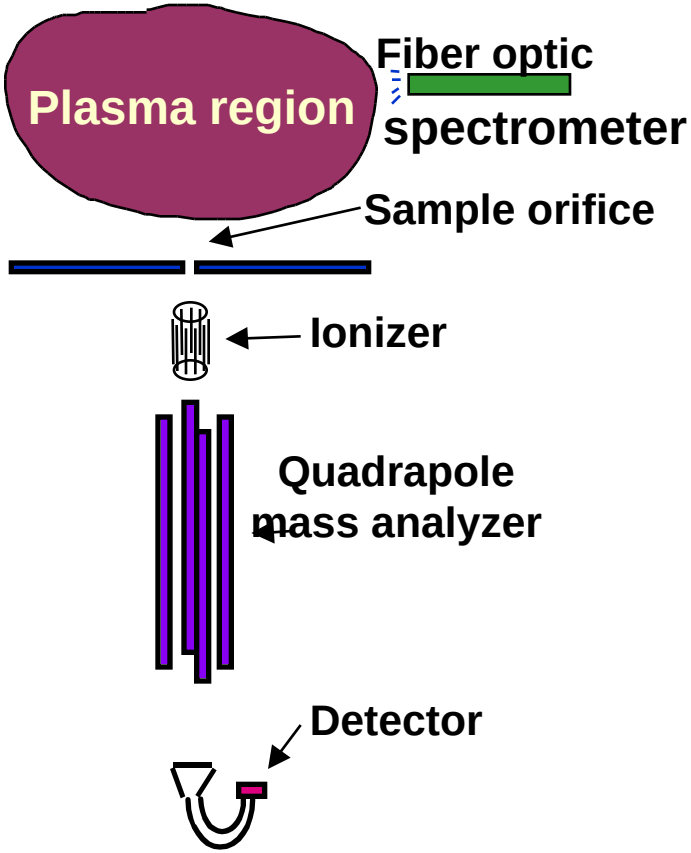


$Ta_2(OC_2H_5)_{10}$ + 2 $CF_3COCH_2COCH_3$ ----->
2 Ta $(CF_3COCHCOCH_3)(OC_2H_5)_4$ + 2 C_2H_5OH

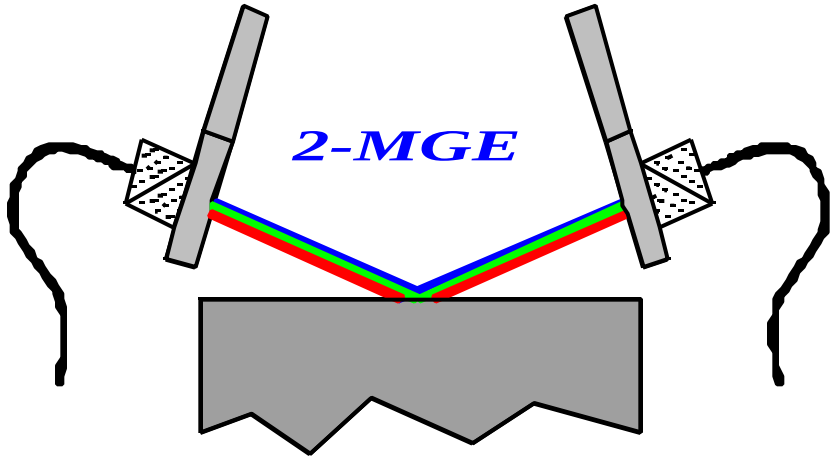
- Yellow, non-viscous liquid
- Bp = 90 ºC at 1 torr
- Reacts slowly with atmospheric moisture, stable in bubbler
- First synthesized by: Pollard and Puddephatt, ***Chem. Of Mater***., **11**, 1069, (1999).
- During process, bubbler kept at 102 C, heated gas ring at 110 C

Mass and Optical Emission Spectroscopy: Determining critical process chemistry

- Determine key reactions
  - kinetics of atom-molecule reactions
  - Identity and lifetimes of intermediate species
- Direct correlation of gas-phase species with film properties
- Mass spec: UTI 100C
- Optical emission spec:
  - WPI SD1000
  - Czerny-Turner (1 meter)
- Only OES reported here

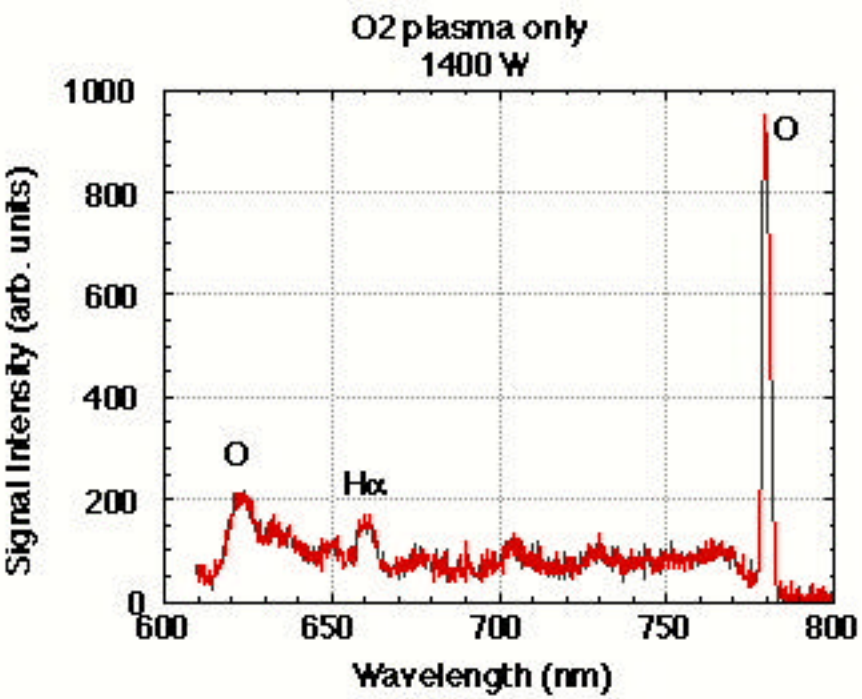


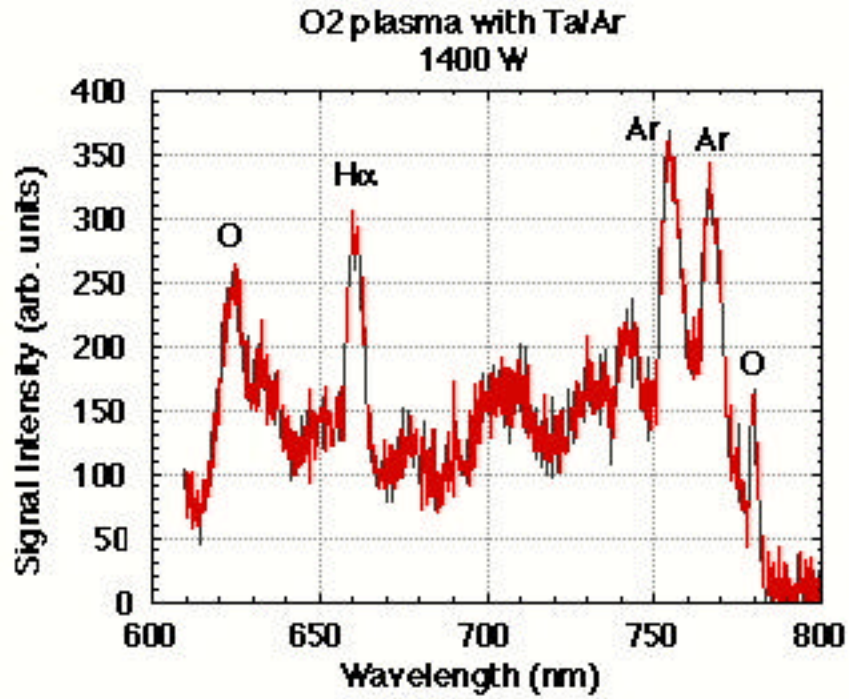
Several techniques are used for determining film properties



- Optical properties are determined by 2-Modulator Generalized Ellipsometry
  - Two polarizer-photoelastic modulator pairs: PEM's operating at 50.2 and 60.2 kHz
  - Measures 8 parameters (other spectroscopic ellipsometers measure 2)
  - Spectroscopic Ellipsometry used to determine film thickness, surface roughness, optical functions of films (band gap and refractive index)
  - Additional capabilities of 2-MGE: Anisotropic bulk materials and films
  - Wavelength range: 250-850 nm (4.96 to 1.46 eV)
- Auger emission spectroscopy used to determine Tantalum to Oxygen ratio

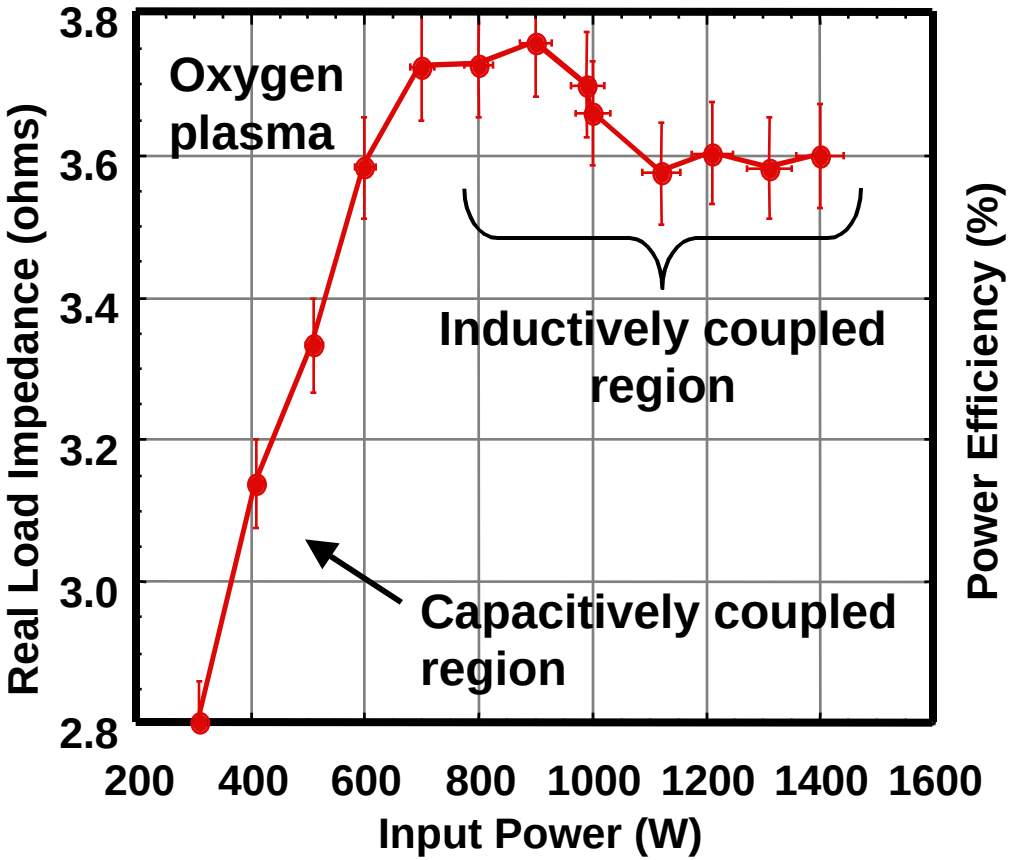
Optical Emission shows excited species in plasma

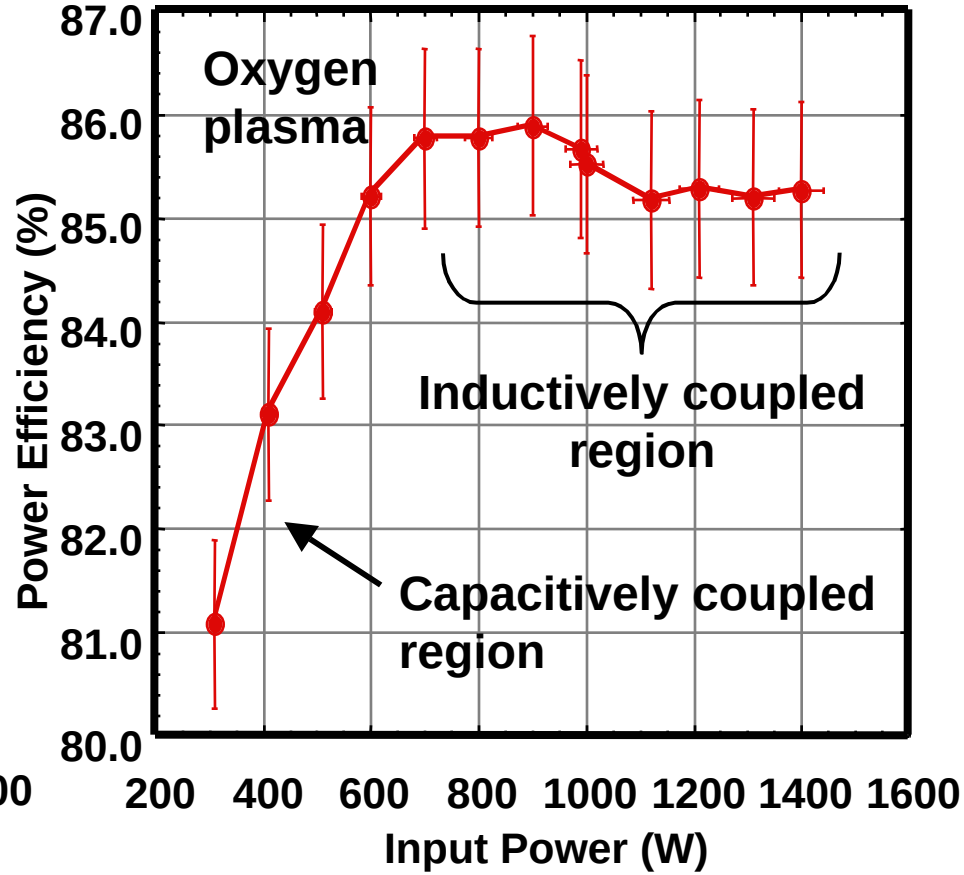




- The Hα line increases with Ta/Ar precursor flow
- Little if any emission from F, C, etc.: need to check with Cherny-Turner spectrometer for more detail and also correlate with mass spectrometer

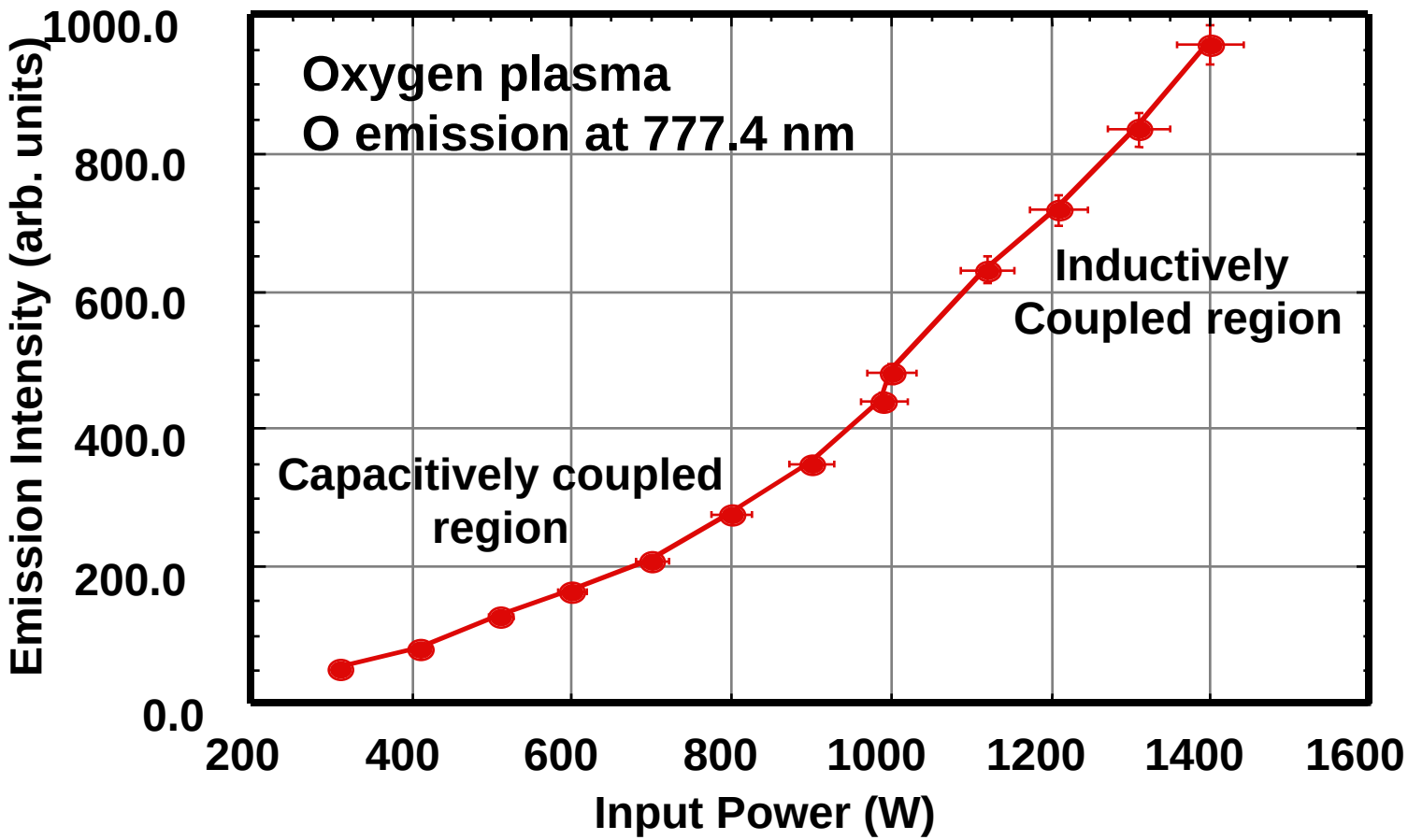
Electrical characteristics of system show processing regimes





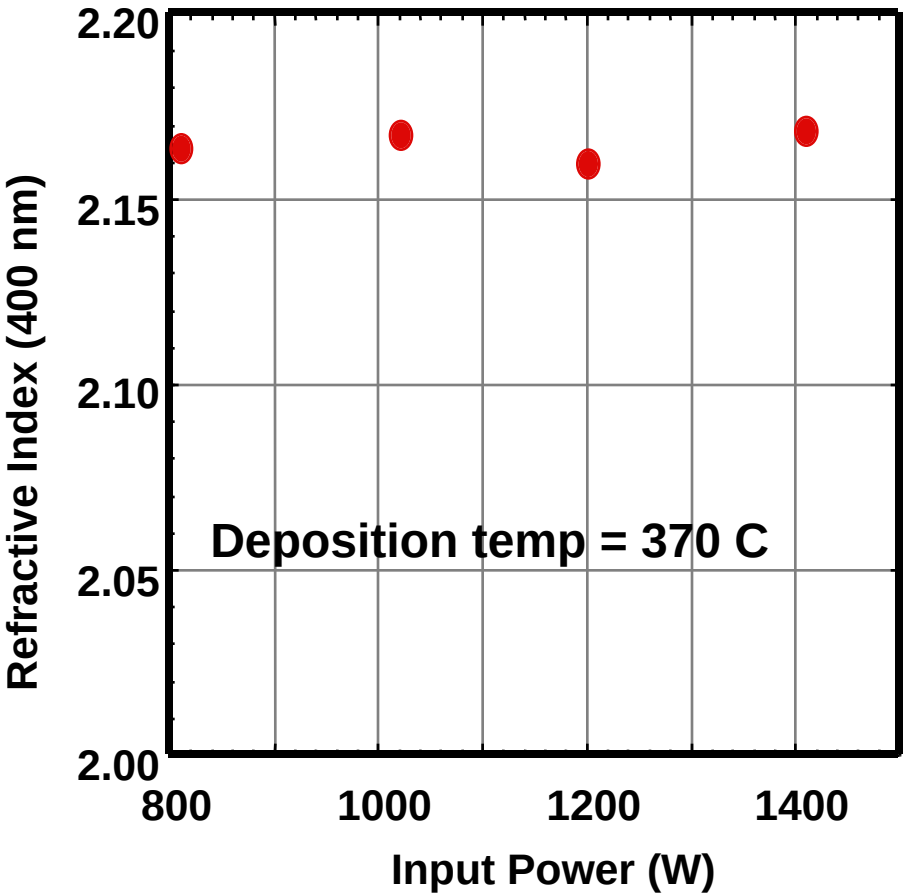
- The capacitively coupled region is characterized by a low density plasma with high plasma potentials
- The inductively couple region is characterized by a high density plasma with lower plasma potentials: gives high flux of reactive atomic species

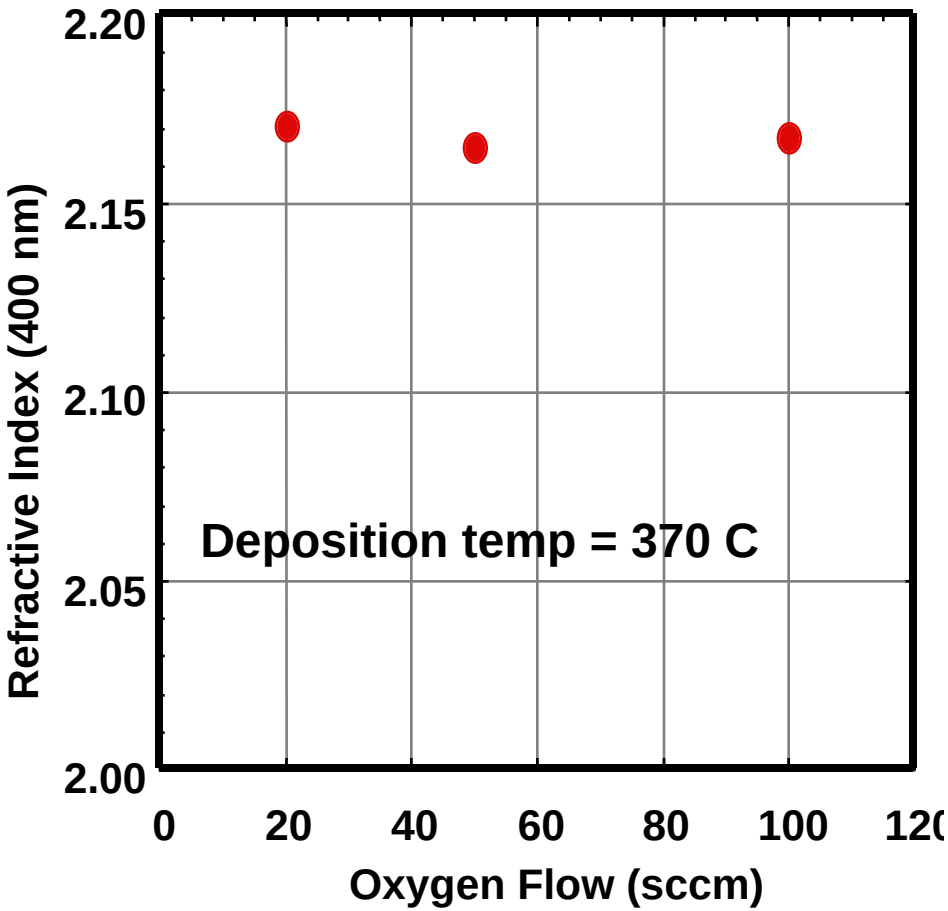
The oxygen emission is highest in the inductively coupled region



- The atomic oxygen emission intensity increases at a higher rate in the inductively coupled regime: increased density
- Processing was concentrated in this regime

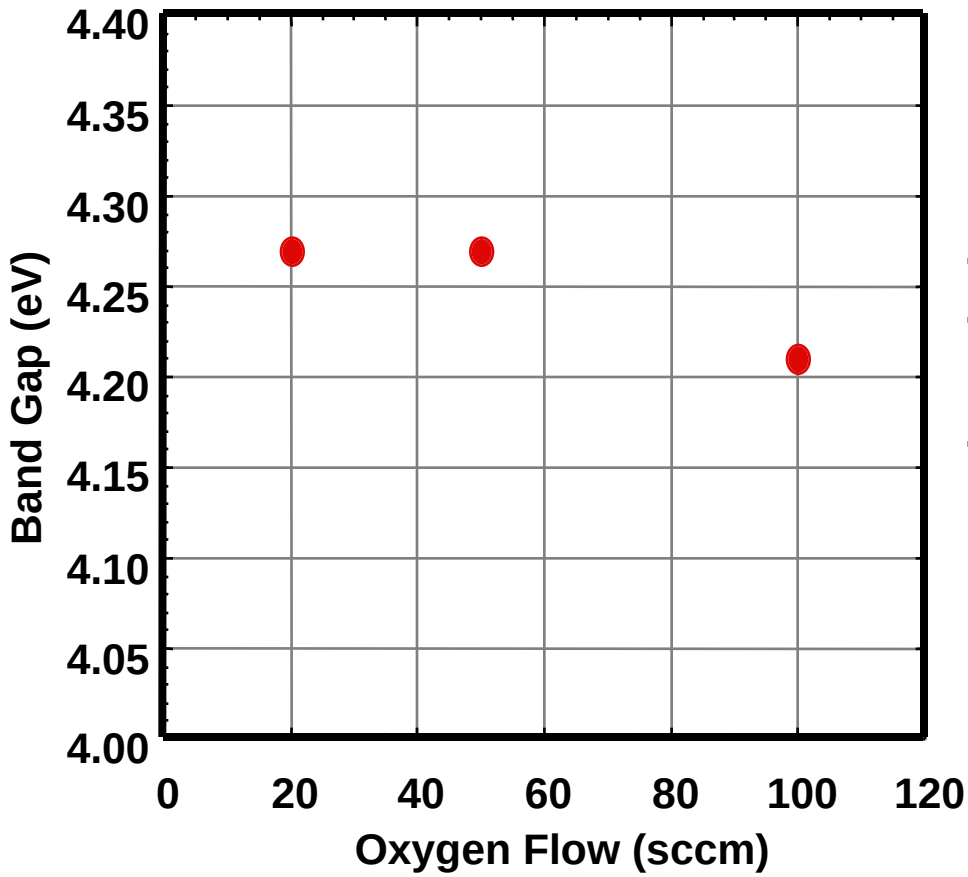
Refractive Index vs conditions

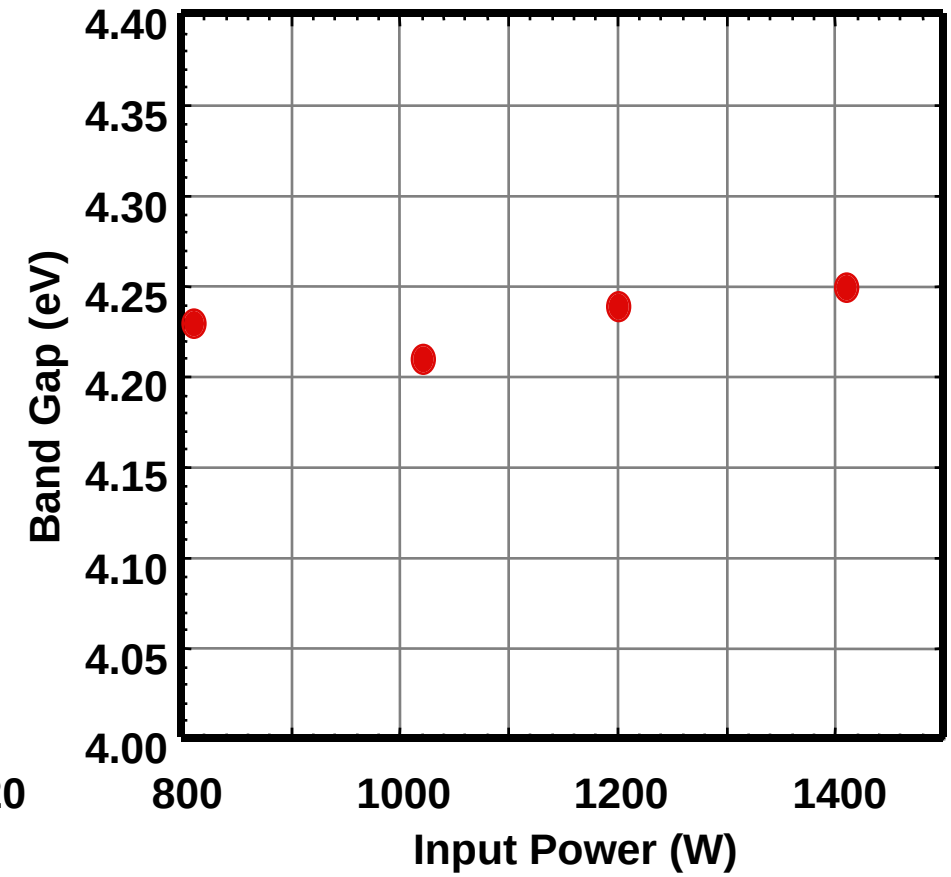




- The refractive index of the films is very consistent as a function of processing conditions: not very sensitive to power or O2 flow
- At 400 nm, the index is 2.16 - 2.17: good contrast of silicon dioxide

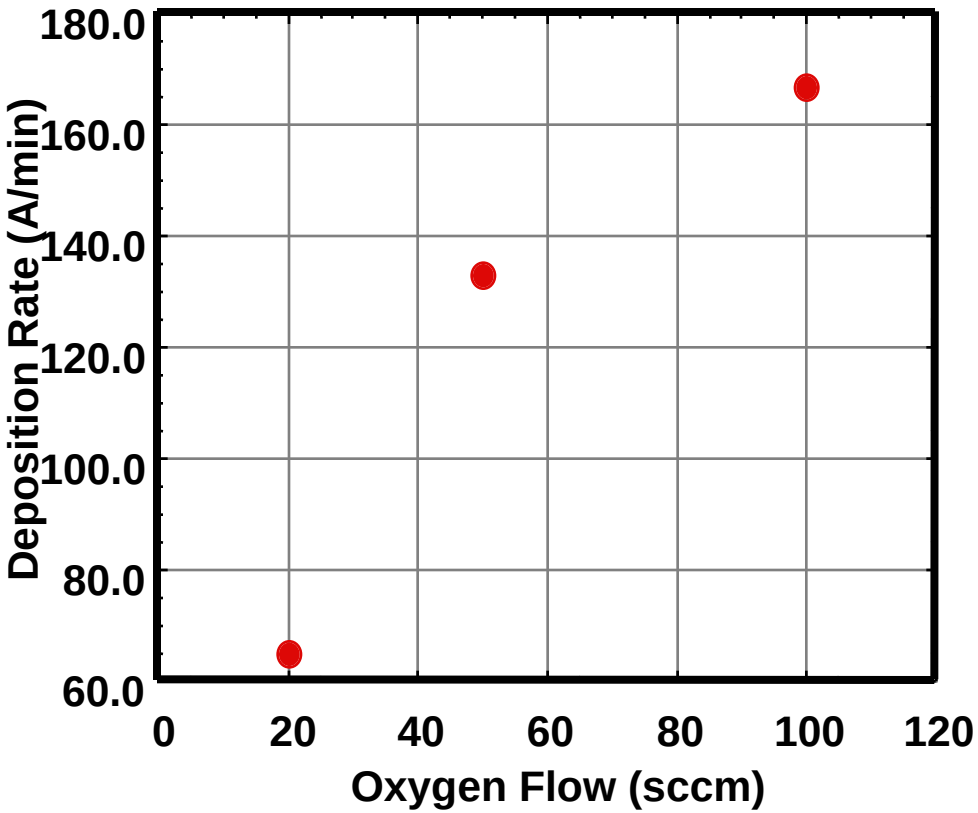
Band Gap vs conditions

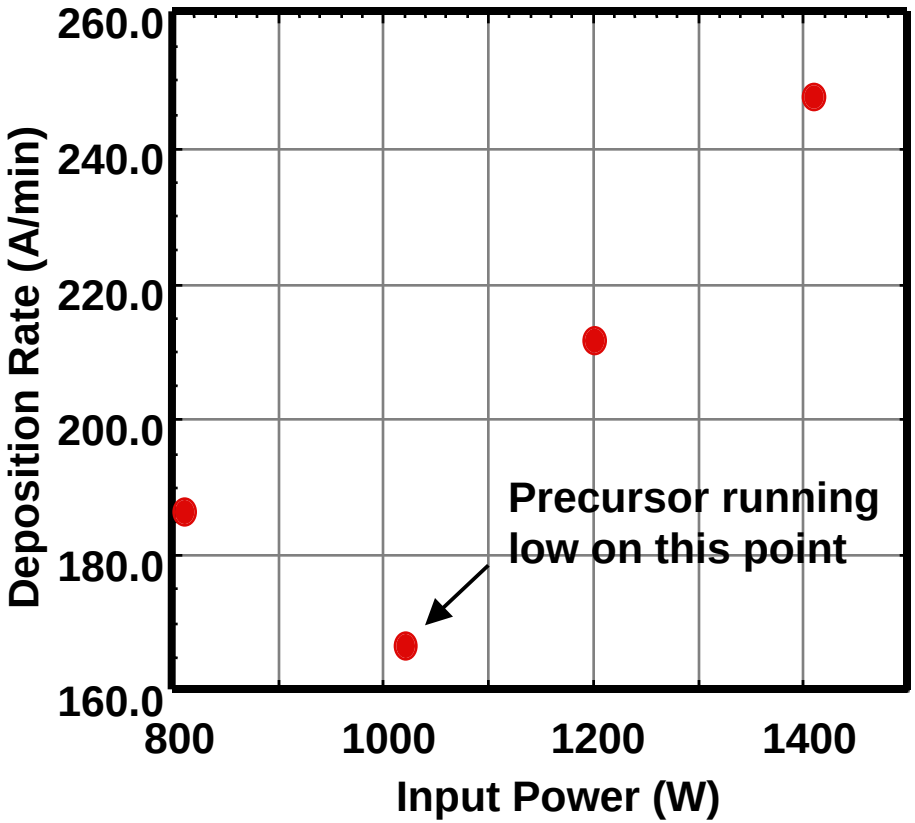




- The band gap of the films is also very consistent as a function of processing conditions: not very sensitive to power or O2 flow
- Band gap varies from 4.21 - 4.25 eV: good for blue light emitters

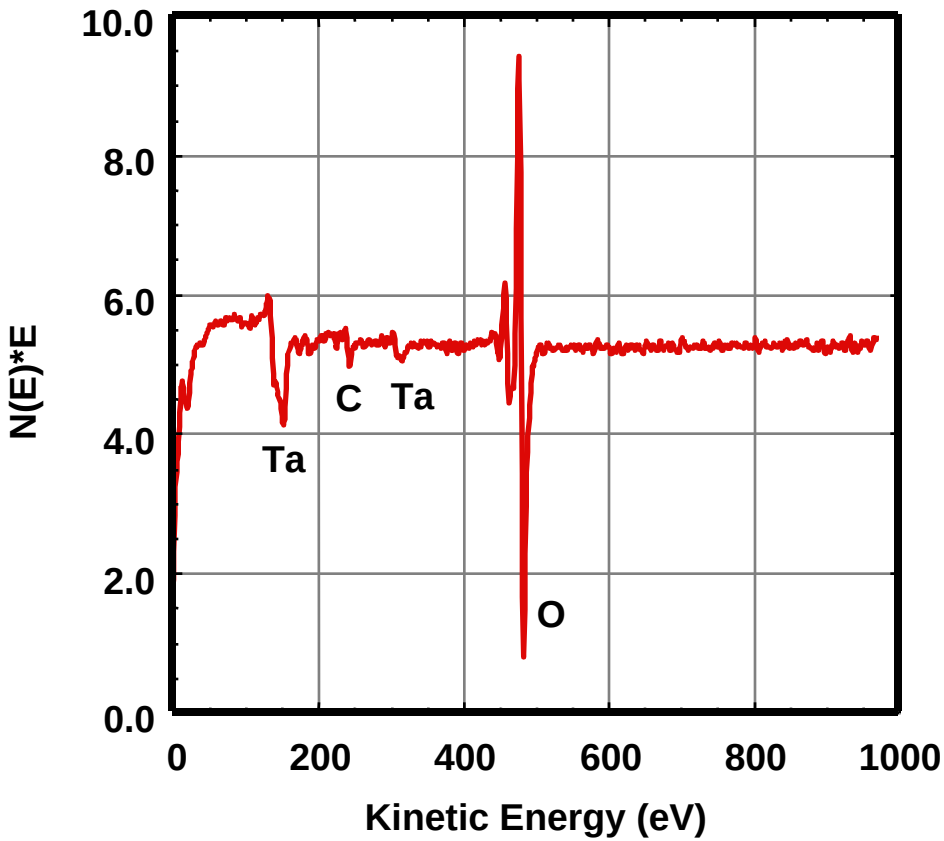
Deposition rate vs conditions

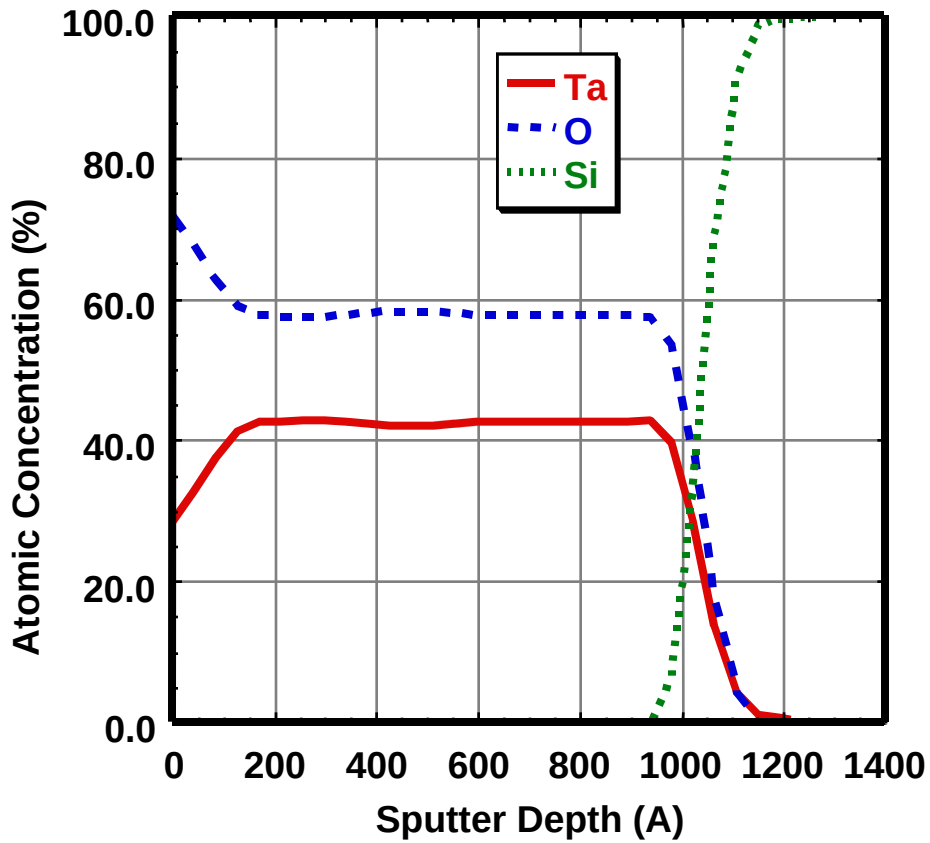




- The deposition rate increases with oxygen partial pressure
- In general, the deposition rate also increases with power: the more atomic oxygen, the better

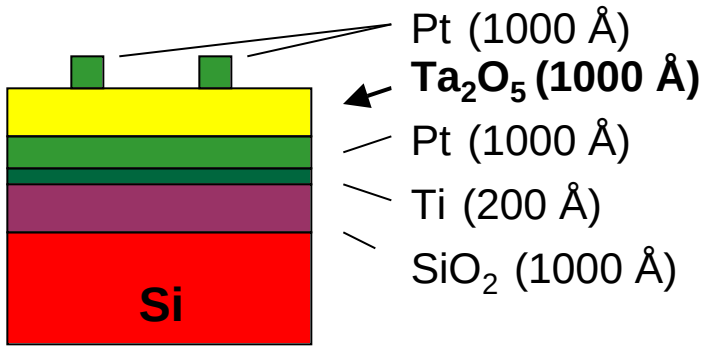
Auger results show a uniform film





- Auger analysis shows that the films are uniform after the first 100 A
- No carbon or fluorine contaminants detected in the bulk film: detection limit is 2 atomic percent
- Ta/O ratio is 0.4: stoichiometry is correct

Electrical measurements show that the film is a good dielectric



- MIM capacitor
- Dielectric constant = 29 +- 1 at 10^6 hertz
- Breakdown field > 10 MV/cm

Summary

- **Process for TaOx deposition is progressing**
  - **Plasma source is producing the desired levels of atomic species**
  - **Process seems fairly robust**
- **Quality of the films is encouraging**
  - **Refractive index of 2.16 - 2.17 at 400 nm**
  - **Band gap of 4.21 - 4.25**
  - **Low (if any) impurity content in bulk film**
  - **Electrical characteristics look good: dielectric = 29, breakdown > 10 MV/cm for 1000 A film**
- **Next step: More detailed gas phase analysis**
  - **Use Czery-Turner optical spectrometer to look at details of emission**
  - **Correlate OES data with mass spectrometer results**