# Dielectric Properties of Silicon Nitride Deposited by High Density Plasma Enhanced Chemical Vapor Deposition

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**Oak Ridge National Laboratory**

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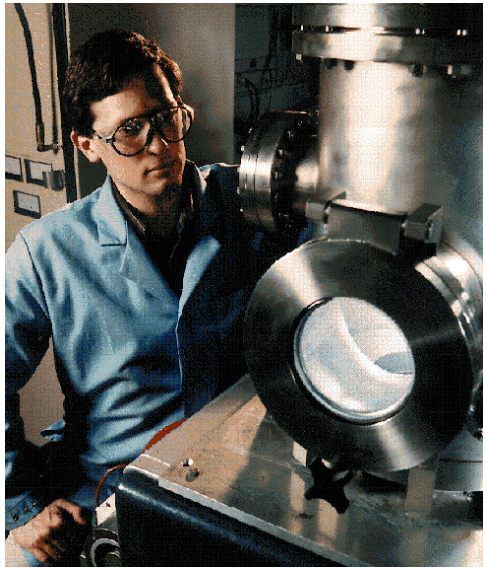
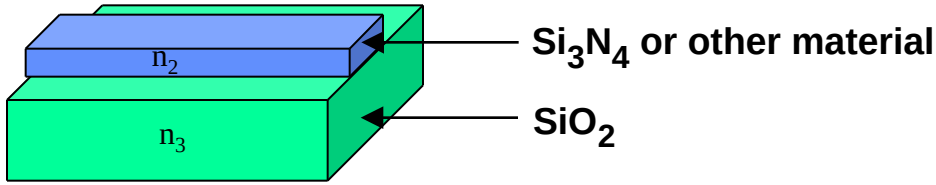
# Agenda

- Motivation: develop waveguide materials for on-chip optical interconnect applications
- Inductively coupled high density plasma source description
- Gas phase diagnostics using mass spectrometer
- Results
  - Refractive index and bandgap vs deposition conditions: want n>2, BG>4
  - Increase process window by H2 addition
  - Decrease in hydrogen content and improved stoichiometry with H2 addition
- Summary

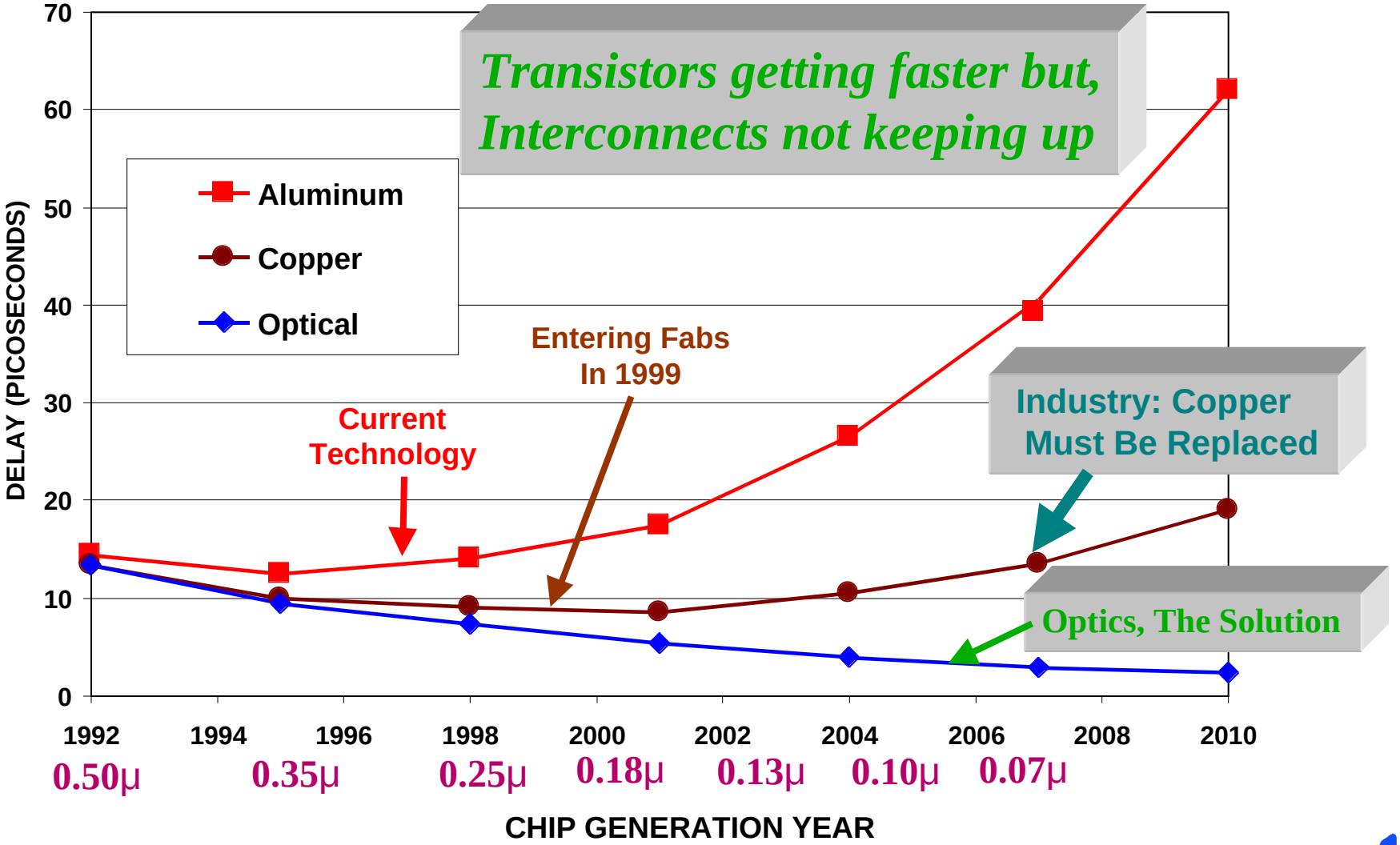


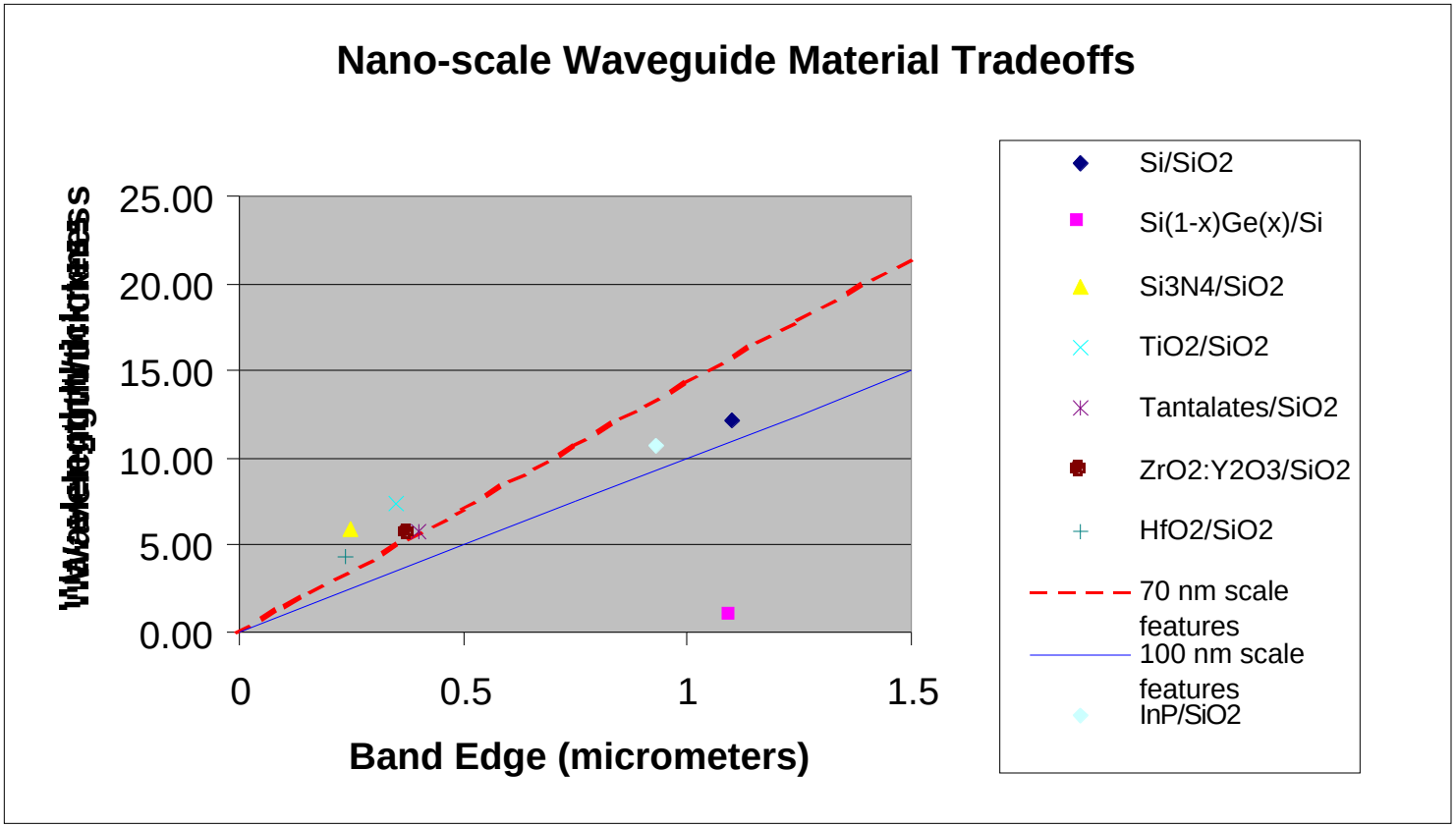
# We are Addressing the Science Issues Related to Advanced Optical Interconnect (OI)Technology

- 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
  - Hosting 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



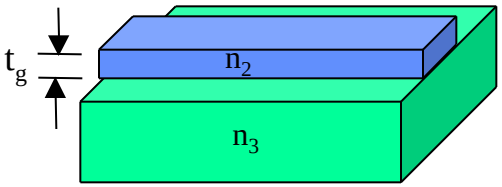
# Optical Interconnect Is A Viable Solution Beyond Copper





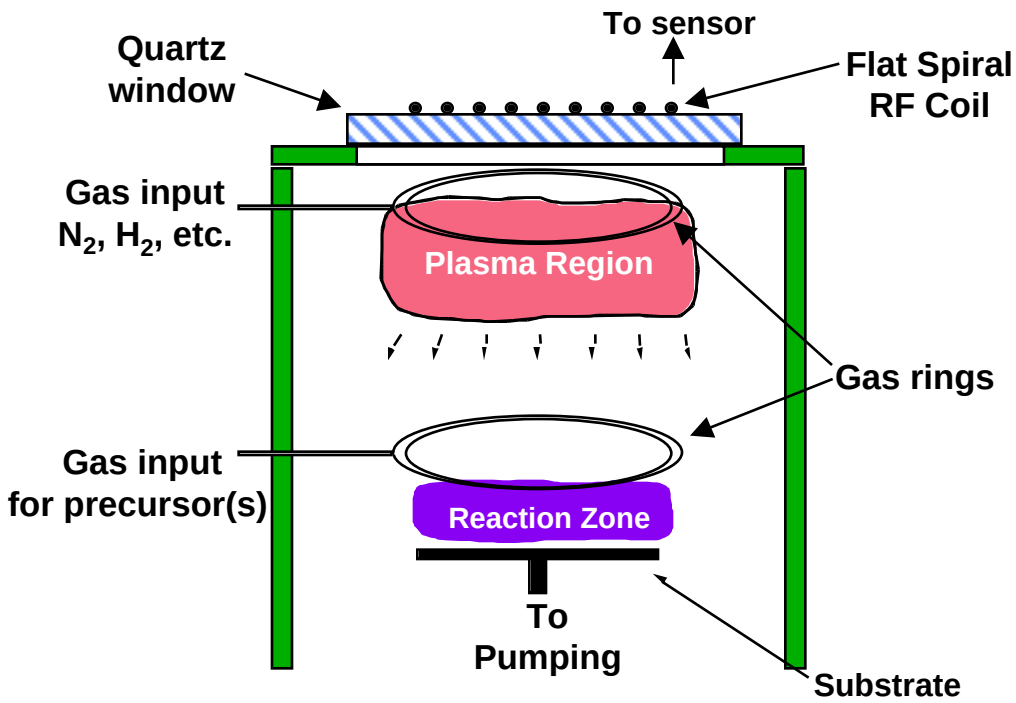

**Governing equation for assymetric waveguide**

$$\Delta n = n_2 - n_3 > \frac{(2m+1)^2 \lambda_0^{\,2}}{16(n_2+n_3)t_g^{\,2}} \qquad m = 0,1,2,3,\ldots$$



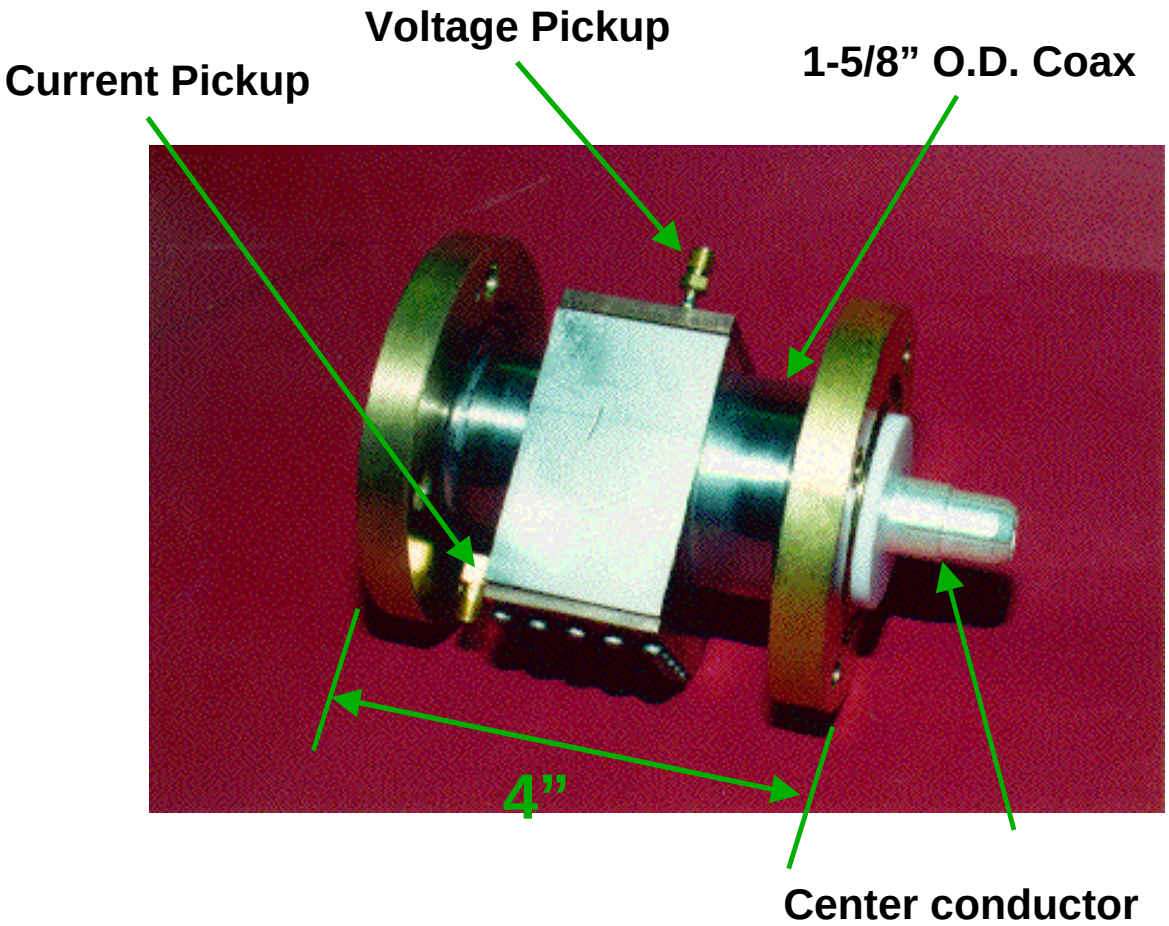
# Our approach uses an inductively coupled plasma to produce reactive species to drive process improvements

- Atomic species produced in high density plasma region
- High efficiency for dissociation of hydrogen (>20%)
- Plasma density and ion energy are decoupled
- Silane (100%) is injected from a gas ring downstream (up to 10 sccm)
- Evidence for high flux of atomic species bombarding the surface during film growth
- Low hydrogen incorporation in the film
- Sensor at coil input used to determine power coupling



# Efficiency and loading are measured with a high power sensor

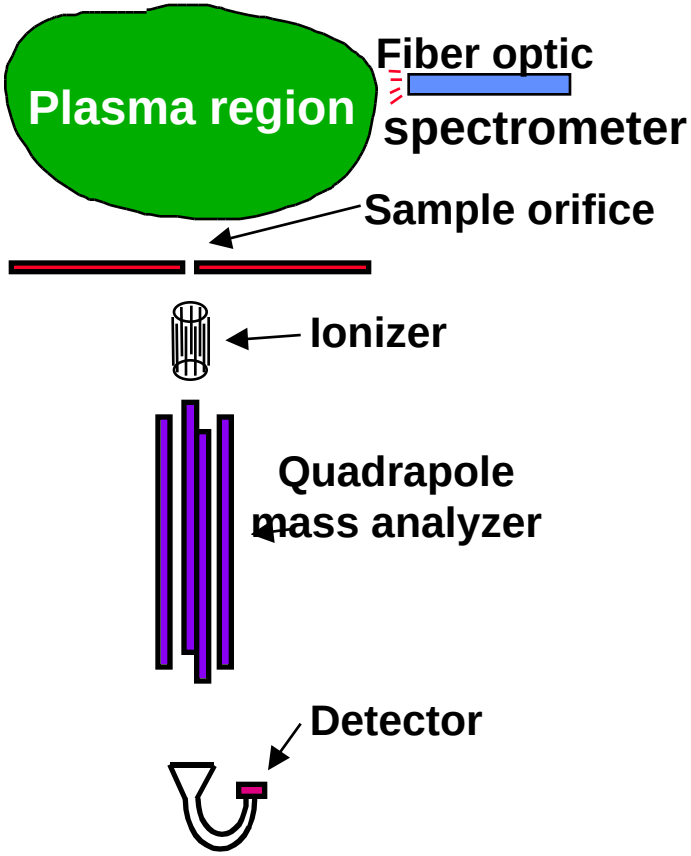
- Capable of handling several 10's of kW of reactive power
- Current pickup via Faraday shield in outer conductor of coaxial line
- Voltage pickup via small disc capacitively coupled to center conductor
- Machined from a solid piece of stainless steel and nickel plated to give a through impedance of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



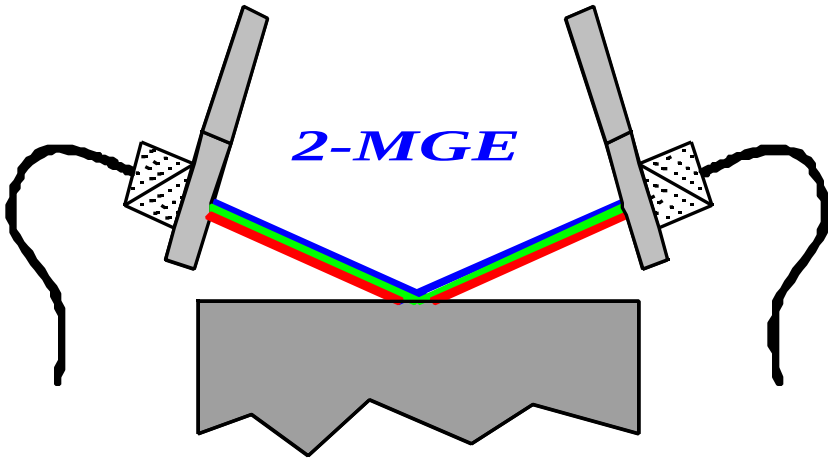

**Sensor located at input of coil**

# 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 prpoeries
- Allow us to be proactive in selecting process conditions that lead to quality film growth

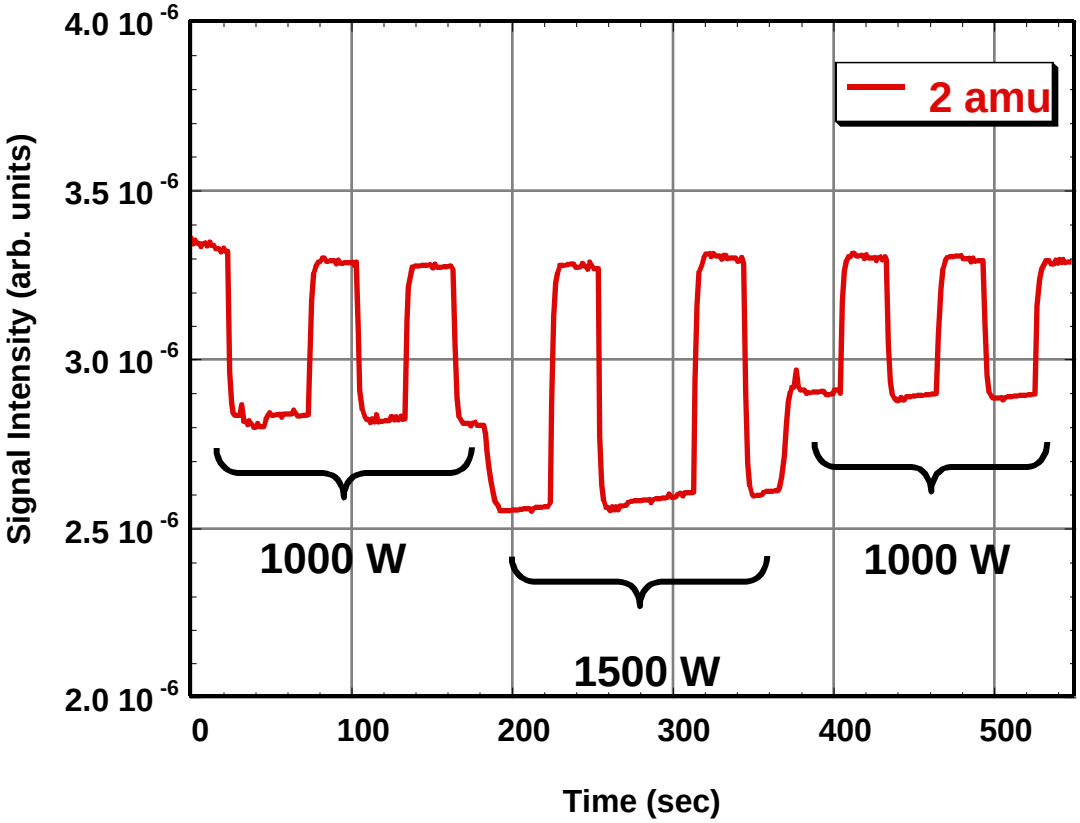


# Several techniques are used for determining film properties




- 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)
- Rutherford Backscattering (RBS) and Hydrogen Forward Scattering (HFS) are used to determine composition (N/Si ratio) and hydrogen content (Charles Evans)
- FTIR also used

# Hydrogen dissociation can be estimated by cycling the plasma on/off




**H2 Plasma only**

Plasma off level

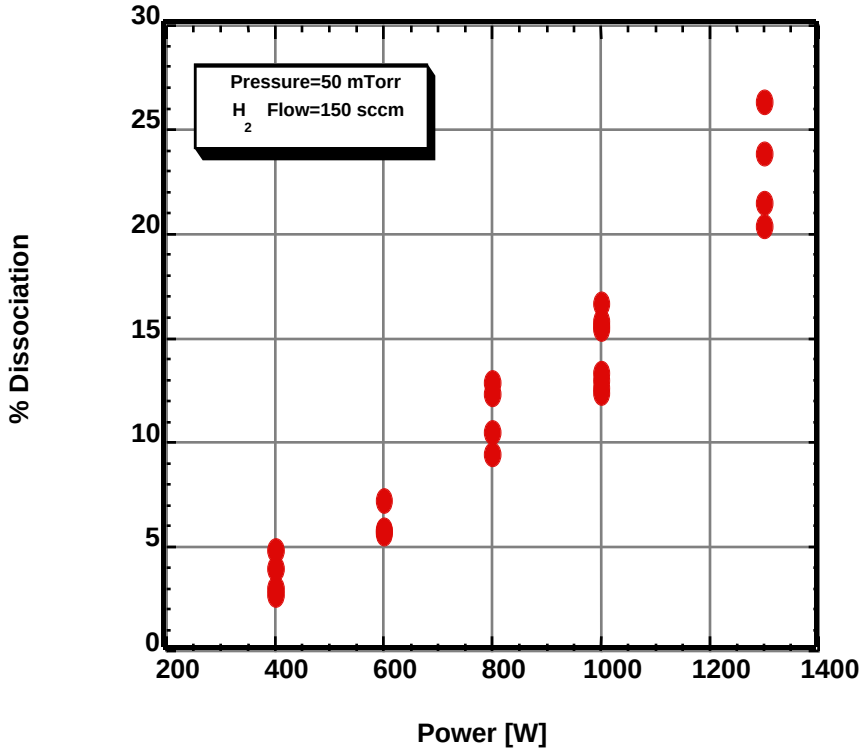
% Change = % Dissociation

Plasma on level (1000W)

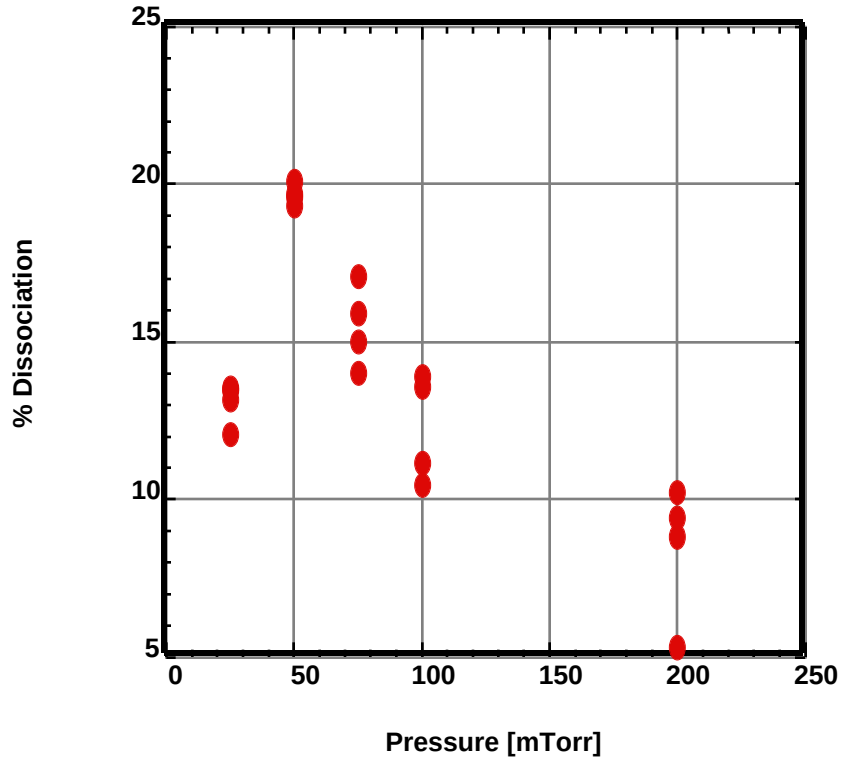
- The amu = 2 signal change when the plasma is turned on is related to the production of atomic hydrogen: H2 → H + H
- Recycling and recombination at the chamber surfaces will have the effect of increasing the hydrogen signal when the plasma is on: surfaces can act as a source for H2
- Method determines a lower limit for dissociation

# Hydrogen dissociation increases with power and is peaked near 50 mTorr

**Pressure = 50 mTorr, 150 sccm H2**

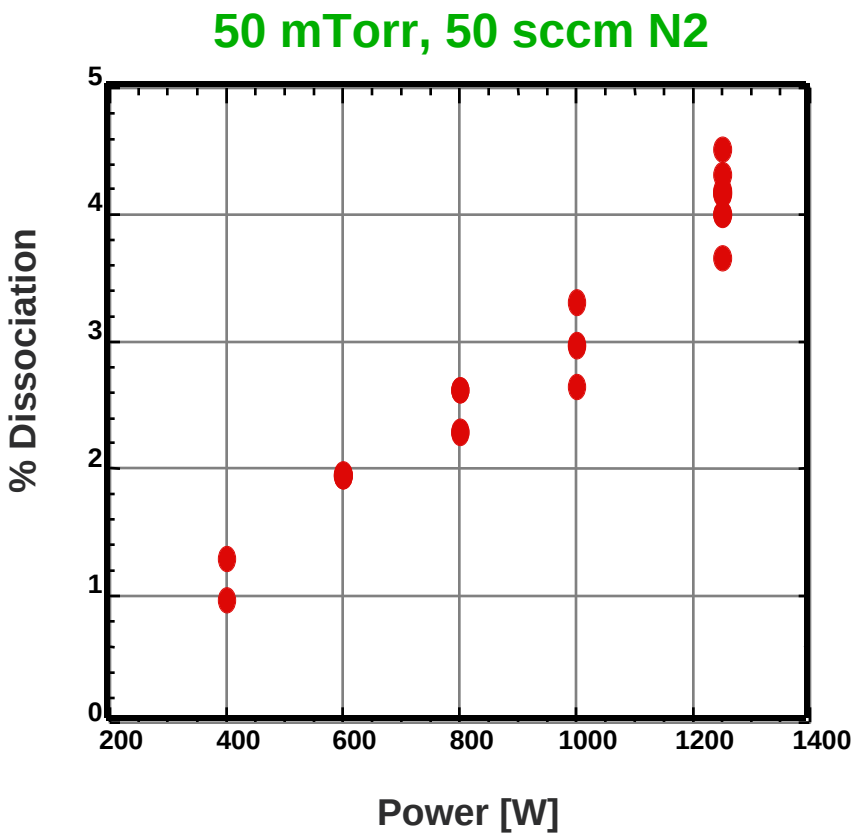


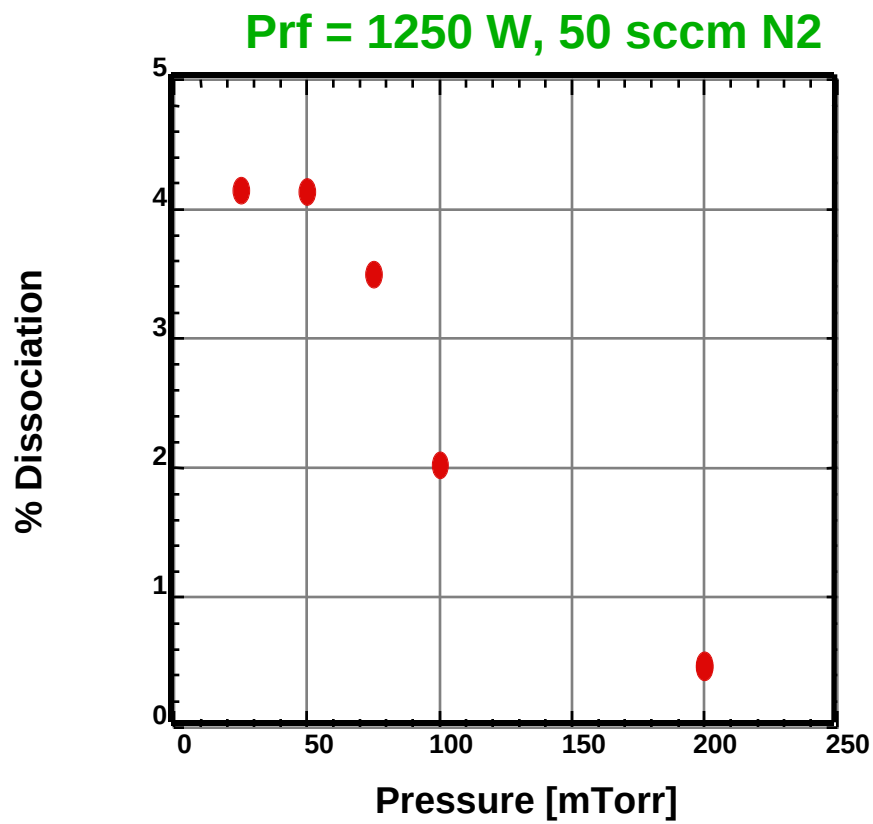

**Power = 1250 W, 150 sccm H2**




- Both cases are for a 100% Hydrogen plasma
- Most deposition has concentrated on operating around 50 mTorr

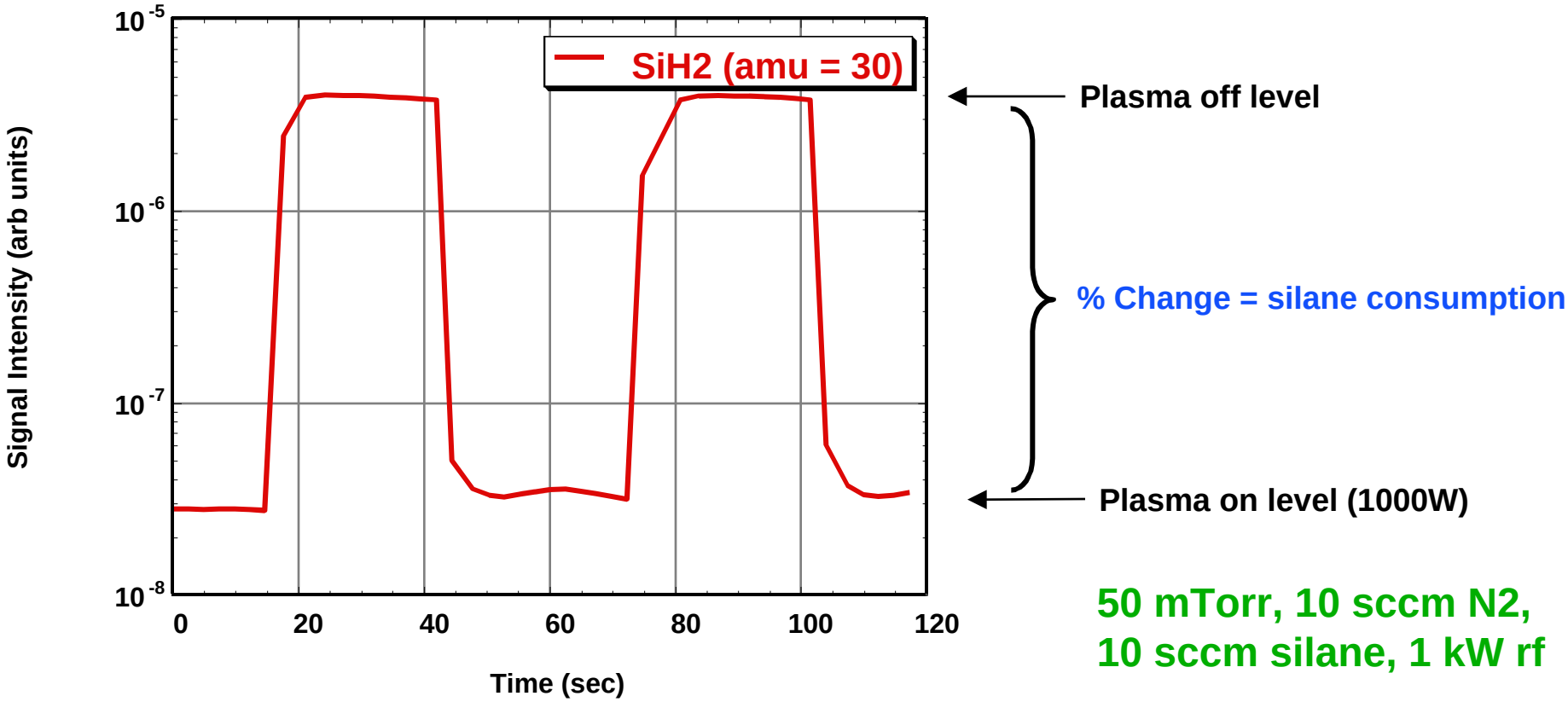
# Dissociation of nitrogen is less than that of hydrogen




- 100% nitrogen plasma
- Similar trend to hydrogen
- Dissociation energy higher for nitrogen: percentage is therefore less

# Silane consumption can also be estimated by cycling the plasma on/off

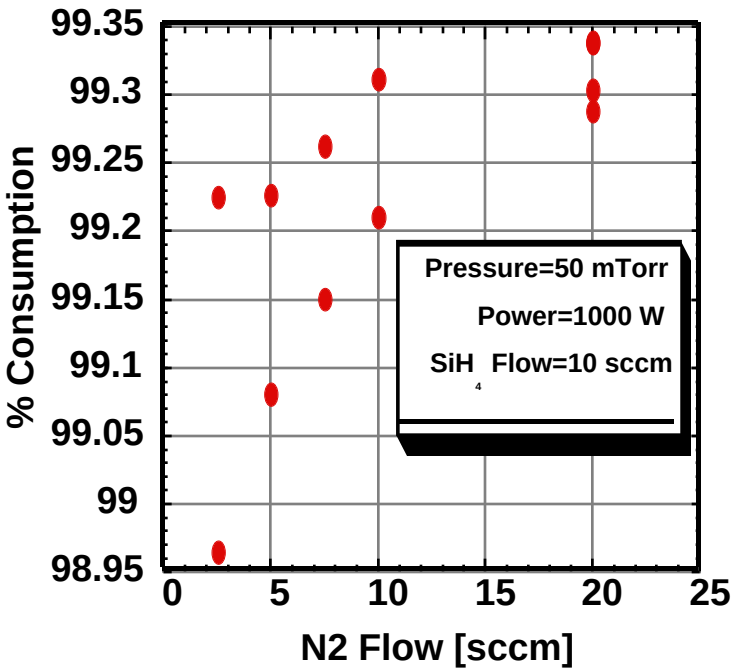



**50 mTorr, 10 sccm N2, 10 sccm silane, 1 kW rf**

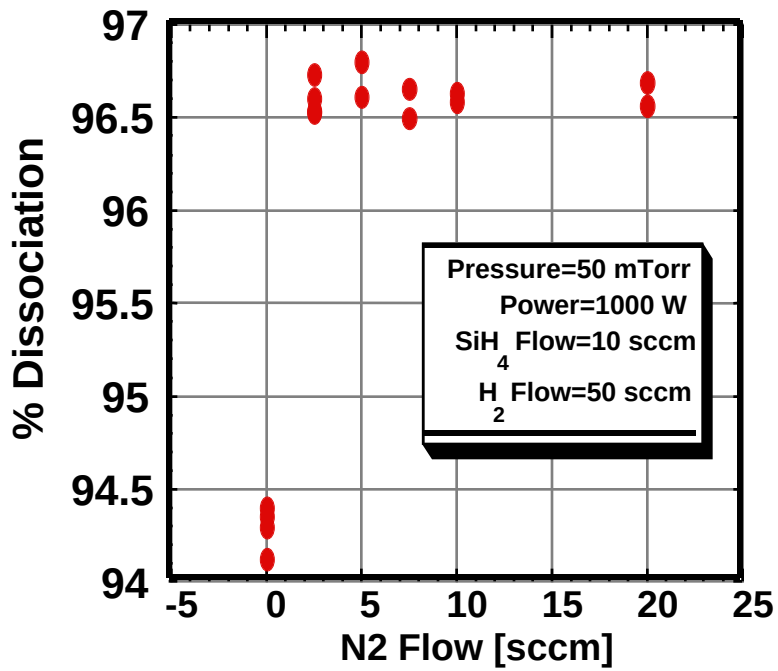
- The mass 30 intensity, created when silane enters the ionizer of the mass spectrometer, is related to the silane flux
- Decrease in the mass 30 intensity (SiH2) with the initiation of the plasma is related to the consumption of silane in the deposition process
- Consumption of >90% is typical for our process conditions

# Silane consumption is high for our processing conditions

**No H2 gas added**

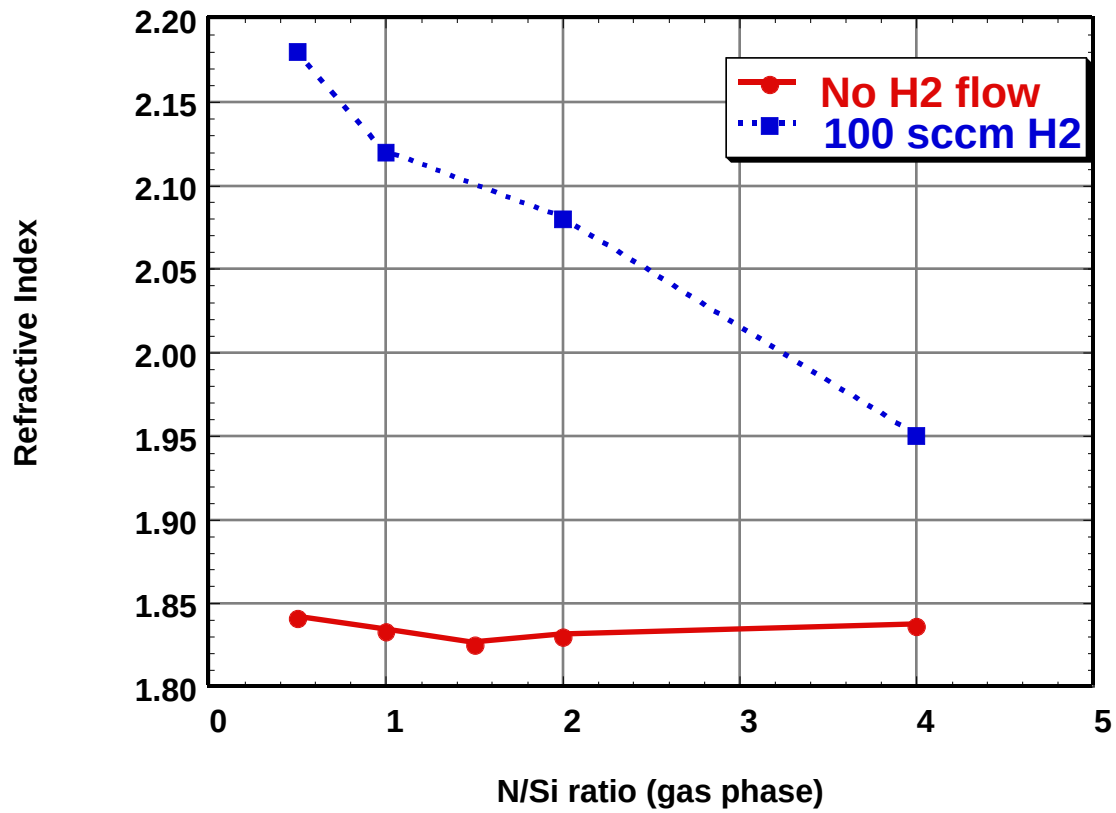



**50 sccm H2 gas added**




**The high density plasma effectively breaks up silane**

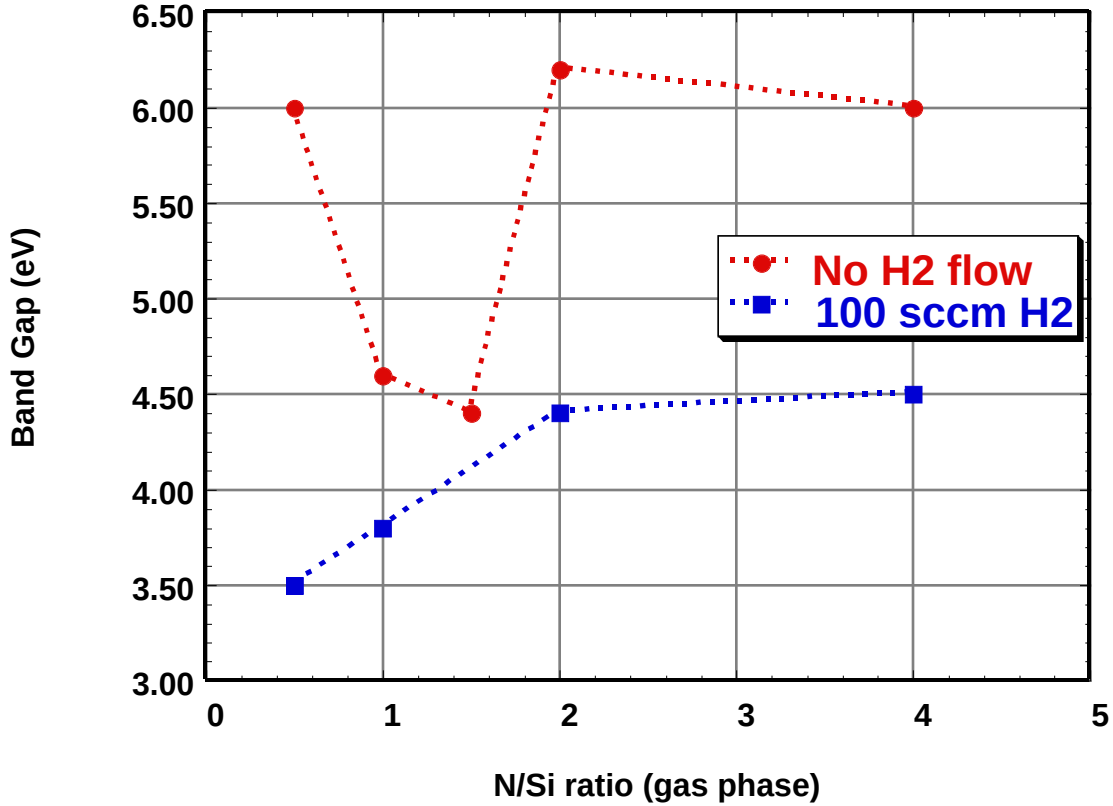
# Refractive index changes little until H2 gas is added in the plasma region




Prf = 1000 W
Silane = 10 sccm
Substrate = 380ºC

- Without hydrogen addition, the refractive index does not vary much as a function of nitrogen/silicon gas flow
- 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

# The bandgap decreases with H2 gas addition




Prf = 1000 W
Silane = 10 sccm
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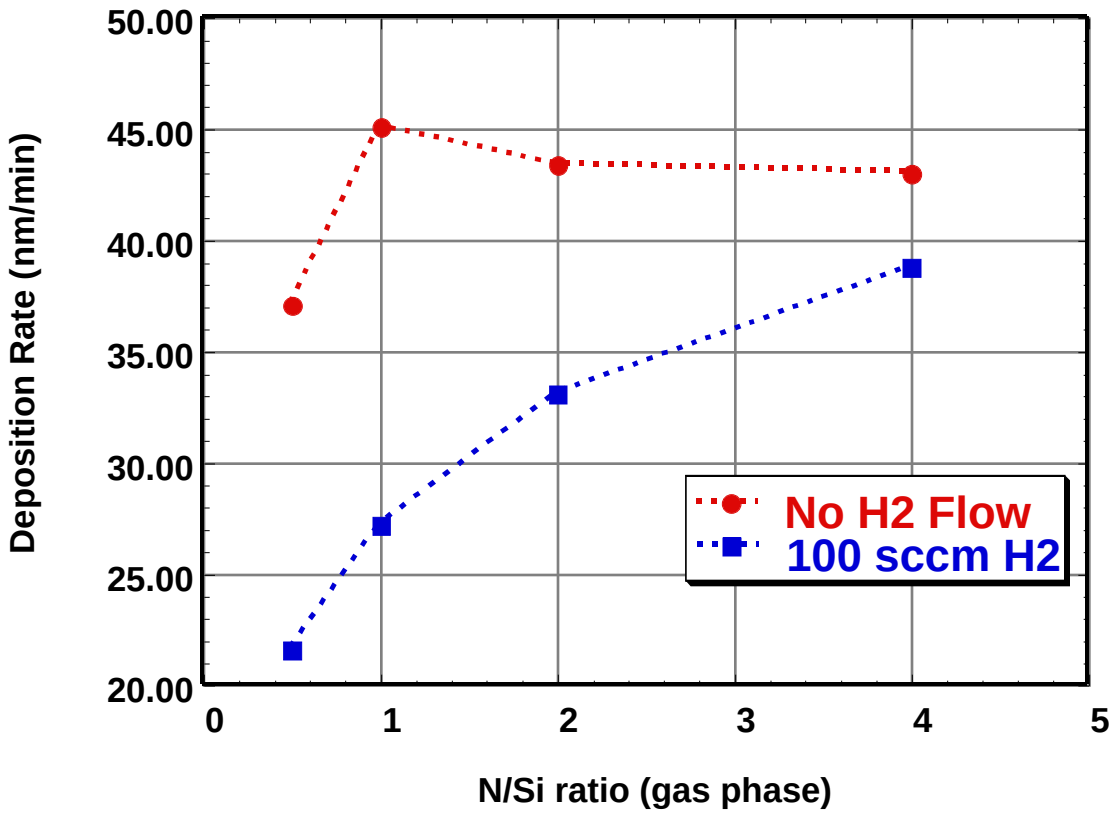
- With hydrogen addition, the bandgap increases with nitrogen gas flow
- The goal of a band gap > 4.0 eV with a refractive index > 2.0 can be achieved by the addition of hydrogen in the gas phase

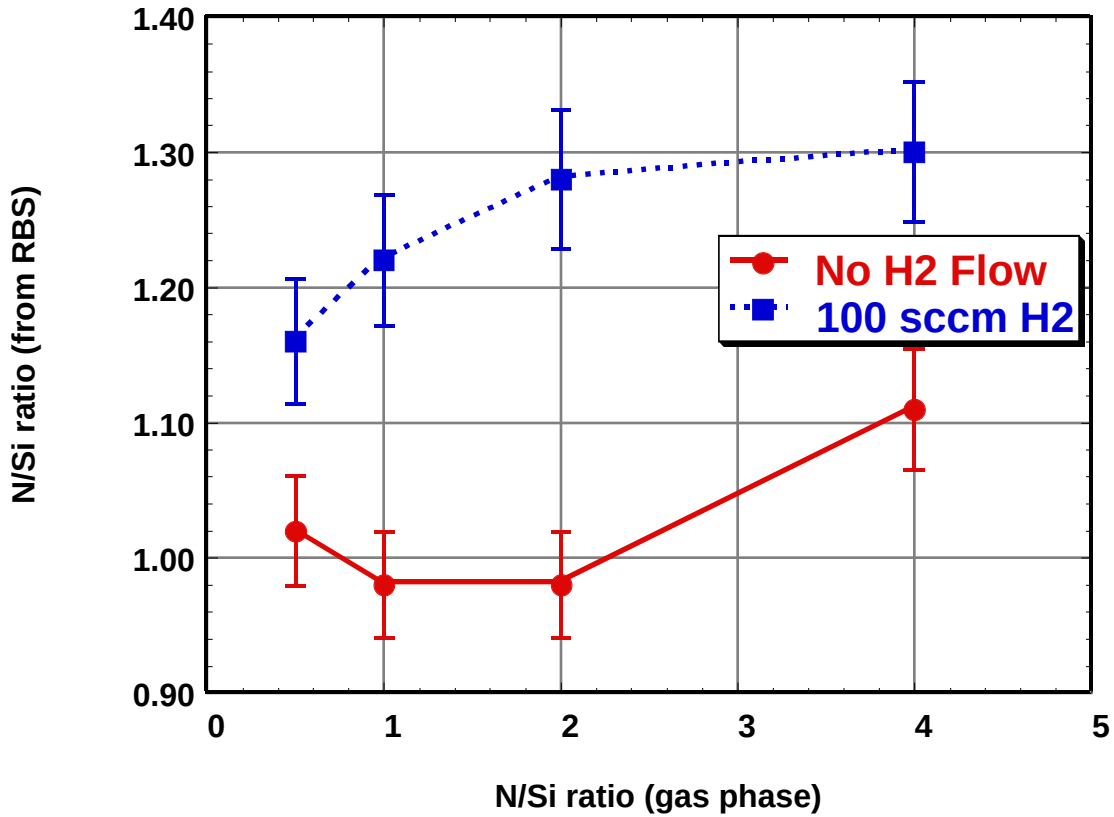
# Deposition rate varies from 20-45 nm/min




Prf = 1000 W
Silane = 10 sccm
Substrate = 380ºC

- The flux of atomic hydrogen etches the film and reduces the effective deposition rate
- The rate increases as the nitrogen flow rate increases (for the H2 gas addition case)

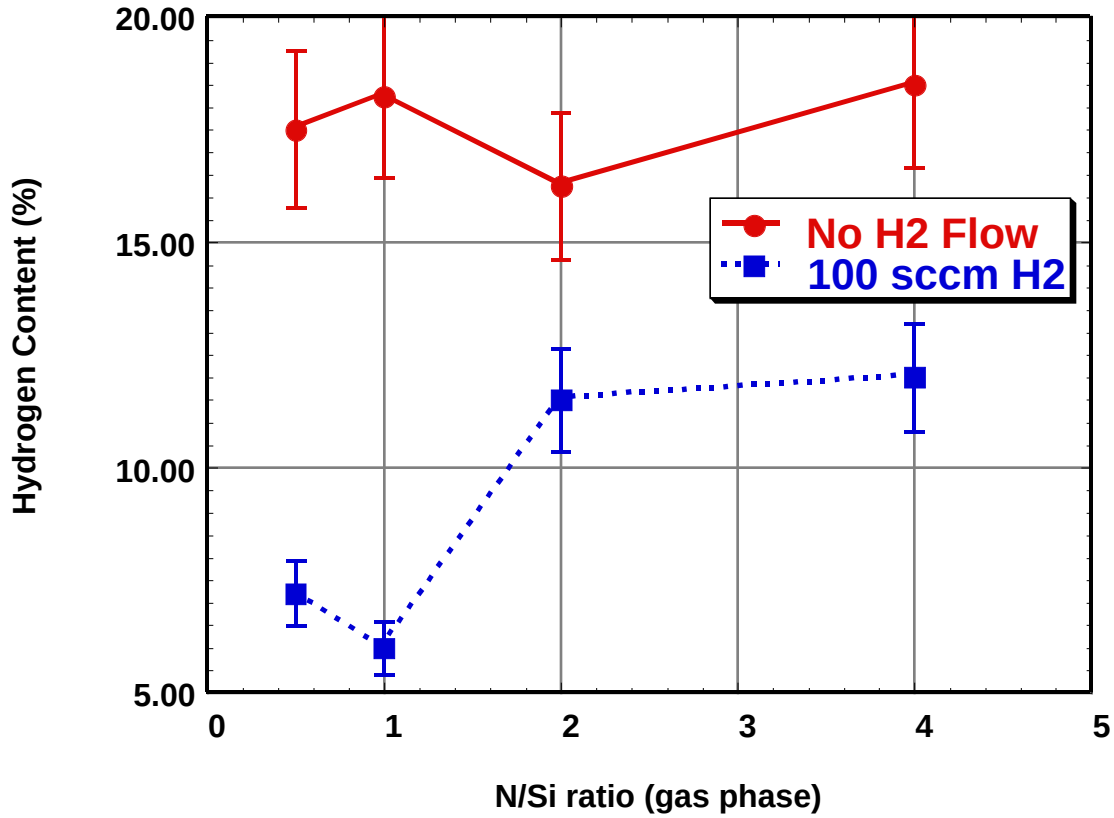
# Films are silicon rich, but stoichiometry can be achieved with H2 addition




Prf = 1000 W
Silane = 10 sccm
Substrate = 380ºC

- Nitrogen/silicon ratio in the film (from RBS) nears stoichiometrically correct value for the hydrogen flow conditions
- Oxygen contamination in the film may also be a contributor to the reduced nitrogen content

# Hydrogen content decreases when H2 is added to the gas/plasma

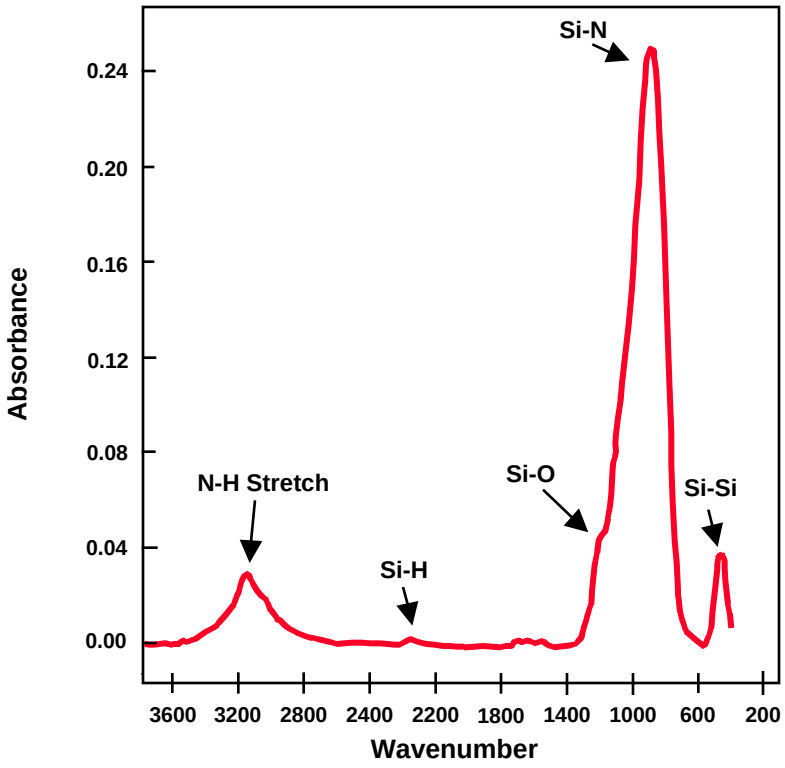



Prf = 1000 W
Silane = 10 sccm
Substrate = 380ºC

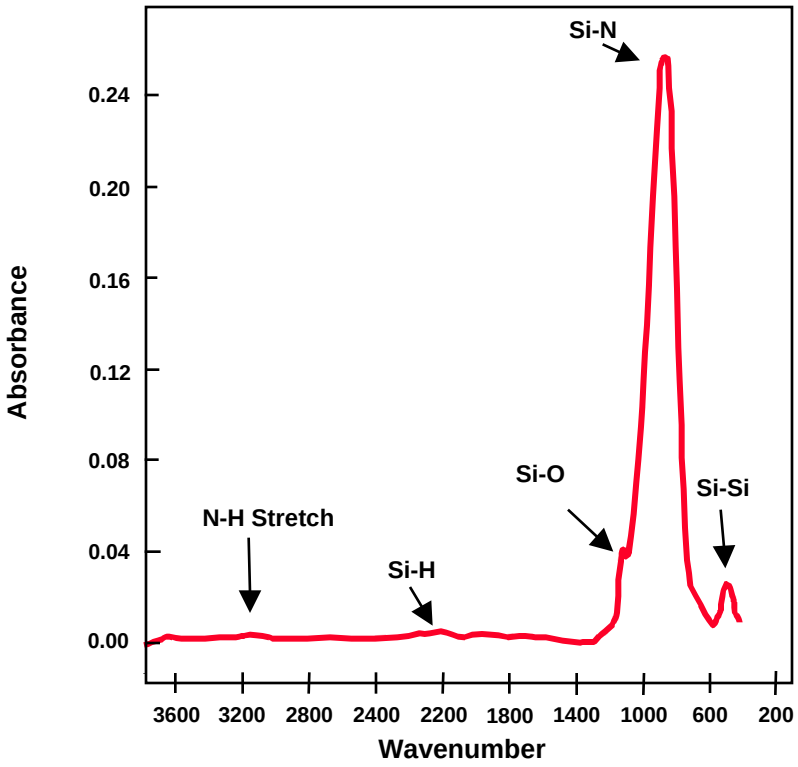
- Hydrogen content determined from Hydrogen Forward Scattering technique (HFS)
- Consistent with abstraction of hydrogen by atomic hydrogen flux at the surface during film growth

# FTIR results indicate that the H incorporation is actually reduced by adding H2 to the plasma

_No $H_2$ flow; N2=Si=10 sccm




_$H_2$ flow=100 sccm; N=Si=10 sccm




- N-H stretch with $H_2$ flow is much lower - less H in film
- Will try to correlate with results from RBS

# Summary

- Process for SiNx deposition is progressing
- Installation of a mass spectrometer in the substrate is helping us to understand effects of process variables on film quality
  - Evidence for substantial hydrogen dissociation and large atomic hydrogen flux
  - Effective silane consumption
- Addition of hydrogen to plasma source region has increased process window
  - Refractive index ranges from 1.82 to 2.18; band gap from 6.2 to 3.5 eV depending on process conditions
  - Deposition rates range from 20 - 40 nm/min
  - Reduced hydrogen incorporation in films
  - Improved stoichiometry
  - Reduced oxygen impurity incorporation
- Next step: tantalum oxide deposition
  - Initial results show refractive index from 2.03-2.29

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