Plasma Diagnostics for Nanoscale Fabrication

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Presentation outline

- Introduction:
  - micro/nano-electronics roadmap
  - diode lasers
- Experimental setup
- Temperature determination
- Simulation of plasma mechanisms
- Estimation of densities of species
- Conclusions
ITRS functional dimensions

Elementary devices (transistors) per chip

Critical size, nm

Electrons per device

Years


16M 64M 256M 1G 4G 16G

CMOS

* International Technology Roadmap for Semiconductors
Nanotube-based transistor

Carbon nanotubes

- ~20 atoms in circumference, ~2 nm in diam.
- Semiconducting or metallic
- Useful as transistors or interconnects
Nanorods/wires – nanolasers

Lasing output

Excitation

ZnO

$\lambda = 380 \text{ nm}$

Current and future needs

- Advanced process control required
- Must be non-intrusive, compact, and simple
- Monitoring of chemical species:
  - end-point detection
  - process optimization and control
  - contamination “management”
- Local temperature monitoring:
  - plasma uniformity
  - intentionally non-uniform (!?)
Semiconductor process gases

- **Inert** (e.g., Ar, He, N₂)
- **Corrosive** (e.g., HCl, HBr, SF₆, NF₃, CF₄)
- **Highly Toxic** (e.g., AsH₃, PH₃)
- **Pyrophoric** (e.g., SiH₄)
- **Reactive** (e.g., NH₃, N₂O, WF₆, CO₂, O₂)
Impurity transfer

More than 300 technology steps for one chip
High variety of materials in use
How to monitor processes?

- Emission: low resolution, only emitting species
- Absorption: limited if FTIR or UV diode lasers - ideal
- Fluorescence: requires powerful lasers
- Mass spectrometry: intrusive, cumbersome
- Electrical: non-selective
Commercial diode lasers

- InGaAs/GaAs
- AlGaAs/GaAs
- InGaAsP/InP
- InGaAsP/InGaAs or InAsP
- AlGaAsSb/InGaAsSb
- GaN
- ZnSe
- AlGaN/InP/GaAs
- InGaAsP/InP

Doubled frequency

Wavelength, \( \mu m \)

0.3 0.5 0.7 0.9 1.1 1.3 1.5 1.7 1.9 2.1 2.3

Room temperature operation
## Accessible elements

<table>
<thead>
<tr>
<th>Probed already</th>
<th>Possible</th>
<th>Excited only</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al, Ba, Ca, Cr, Cs, Cu, Hg, I, In, K, La, Li, Mn, Pb, Rb, Sm, Sr, U, Y, Zr</td>
<td>Ag, Co, Eu, Fe, Ga, Gd, Hf, Ho, Lu, Mo, Nb, Nd, Ni, Os, Re, Rh, Ru, Sc, Tb, Th, Ti, Tl, Tm, V, W</td>
<td>Ar, As, B, Br, Cl, F, H, Kr, N, Ne, O, P, S, Si, Xe, Zn &amp; etc.</td>
</tr>
<tr>
<td>( \text{H}_2\text{O}, \text{OH}, \text{O}_2, \text{CH}, \text{CO}, \text{CO}_2, \text{CH}_4, \text{NH}_3, \text{HCl}, \text{HBr} )</td>
<td>( \text{N}_2, \text{Cl}_2, \text{F}_2, \text{CF}, \text{CN}, \text{SiF}, \text{AlCl} ) and etc.</td>
<td></td>
</tr>
</tbody>
</table>
Diode laser characteristics

- Tunable over absorption features
- Provide spectrally narrow linewidths
- Compact and simple to use
- Can be multiplexed
- Commercially available
- Relatively inexpensive
Experimental Setup

- Cavity modulation, 1 kHz
- Data acquisition, 20 MHz
- Diode laser scan, 5 min
Simplified Setup

Data acquisition, 0.1 kHz
## Rate of energy loss from cavity

### Reflectance vs. Number of Passes

<table>
<thead>
<tr>
<th>Reflectance</th>
<th>L=50 cm $\tau$ (µs)</th>
<th>L=100 cm $\tau$ (µs)</th>
<th>Number of passes</th>
</tr>
</thead>
<tbody>
<tr>
<td>96</td>
<td>0.04</td>
<td>0.08</td>
<td>25</td>
</tr>
<tr>
<td>99</td>
<td>0.17</td>
<td>0.33</td>
<td>100</td>
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<tr>
<td>99.9</td>
<td>1.67</td>
<td>3.33</td>
<td>1000</td>
</tr>
<tr>
<td>99.99</td>
<td>16.67</td>
<td>33.33</td>
<td>10000</td>
</tr>
<tr>
<td>99.999</td>
<td>166.67</td>
<td>333.33</td>
<td>100000</td>
</tr>
</tbody>
</table>
Etching ICP Reactor

13.56 MHz

100 kHz
Diagnostics objectives

- Determination of plasma parameters:
  - gas temperature
  - electron temperature
  - degree of ionization
- Identification of species in etching plasmas
- Measurement of concentrations of species
- Simulation of plasma etching mechanisms based on acquired experimental data
Laser Scan over Argon Line

Plasma:
- 90 mTorr
- 50 W
- 20 µm

Argon line:
- 763.51 nm

Laser:
- VCSEL
- $I_{op} = 4.9 \text{ mA}$
- $\Delta \nu = 5 \text{ MHz}$
- $P_{op} = 0.5 \text{ mW}$
Absorption by Argon Plasma

**Plasma:**
- 200 mTorr, 100 W
- 40 mTorr, 100 W

**Laser:**
- \(I_{op}=4.9\) mA
- \(T=32-20\) C

**Ar line:**
- 763.51 nm

- 450 K
- 550 K
Laser wavelength calibration

Argon and ambient air absorption

Laser scan

Etalon fringe

Wavelength, nm

762.7 762.8 762.9 763.0 763.1 763.2 763.3 763.4 763.5 763.6 763.7

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Ambient oxygen absorption

$O_2 (b^1\Sigma_g^+ - X^3\Sigma_g^-)$
Temperature in Ar/N₂ plasma

- 300 W
- 3% N₂ in Ar
- 45% N₂ in Ar
- 100 W
- 100% Ar
- 3% N₂ in Ar

Temperature, K vs. Pressure, mTorr

0-D model

Doppler temperature
Rotational temperature
0-D simulation in Ar
Temperature in Ar/N₂ plasma

300 W

Temperature, K

Pressure, mTorr

45% N₂ in Ar

3% N₂ in Ar

90% N₂ in Ar

90% N₂ in Ar

Doppler temperature
Rotational temperature

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Argon plasma simulation

![Graph showing temperature and metastable density variations.](Image)

- **Temperature, K**
  - Ranges from 300 to 800 K.
- **Reactant radial dimension, mm**
  - Ranges from -130 to 130 mm.
- **Ar_{ms}** (Ar metastable density, $10^{10}$ cm$^{-3}$)
  - Varies from 0 to 7 $10^{10}$ cm$^{-3}$.
- **T_{gas}** (Temperature)
  - Varies from 300 to 800 K.
- **Power**
  - 100 W
- **Pressure**
  - 100 mTorr
Emission from Ar plasma

![Graph showing emission from Ar plasma with different wavelengths and their relative intensities as a function of pressure in mTorr. The graph includes data points for 763.5 nm, 667.7 nm, 603.2 nm, and 602.5 nm, with corresponding curves indicating the change in relative intensity with pressure.]
Passive Optical Cavity

\[ \lambda = 2.12 \, \mu m \]

Diode Laser

Isolator

Front Mirror

Plasma

Back Mirror on Piezomount

Planar ICP Reactor

PD

Top View

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Composite Spectrum of CF\textsubscript{x}

Wavenumber, cm\(^{-1}\)

Band intensity, m\(^{-2}\)atm\(^{-1}\)

Fundamental, overtone and combination bands
Cavity Modes and Laser Line

- Laser is slowly scanned throughout ~400 GHz
- Cavity length is fast modulated within ±100 MHz

Doppler-broadened line ~1 GHz

Laser scan

<100 MHz

Frequency, MHz

50 kHz

200 MHz
Detection of plasma species

- High anisotropy & selectivity in etching of Si over SiO$_2$ or SiN$_3$ is necessary; research in CF$_x$ radicals plasmachemistry is needed.
- Absolute densities of C$_x$H$_y$, CF$_x$ radicals and kinetics in plasma can be measured by cavity absorption spectroscopy at ~1 km of the equivalent optical pathlength.
- Useful for diagnostics, analysis, monitoring and control of both nano- and microelectronic fabrication processes and development of micro- and nanodevice-based sensors.
Spot Size at Mirrors

Cavity length:
- 0.5 m
- 0.7 m
- 1.0 m

λ = 2 µm; λ = 3 µm

Concentric
Confocal configuration

Spot size, mm

Radius of curvative, m
$v_3$ Fundamental Band of CF$_4$

Emission from CF$_4$ Plasma

Species detected include C, C$_2$, F, CF, Si, O, CO

Impurity Absorption

Interference-free window between 2.1 – 2.2 µm

* M.E. Webber, J. Wang, S.T. Sanders, D.S. Baer, R.K. Hanson, *Proc. 28 Int. Symp. Combustion*
Sensitivity Estimates

- Minimum absorption coeff. $\sim 10^{-10} \text{ cm}^{-1}\text{Hz}^{-1/2}$
- CF$_x$ radicals detection limit $\sim 10^{11} \text{ cm}^{-3}$
  \((\lambda = 2.12 \mu\text{m}; \text{Cavity leakout time} = 100 \mu\text{s})\)

- Single molecule absorption can in principle be detected at strong fundamental bands
  
  \((\alpha \sim 10^{-15} \text{ cm}^{-1}\text{Hz}^{-1/2}; \lambda = 8 \mu\text{m})\)
Conclusions

- Diode lasers operating in the 0.3 - 2.3 µm region are convenient, compact, inexpensive, tunable, of spectrally narrow bandwidth, and require no cryogenic cooling.
- Local and averaged temperature can be determined with different thermometric species.
- Absolute densities of atoms, radicals and molecules can be monitored.
- Multi-parametric measurements possible.
Conclusions

- Checking overall chamber health in real time
- Chamber clean-up/fast start-up optimization
- End-point for small features, cost-effectively
- Dopant species detection for end-pointing
- Monitoring atomic metal species in ALD
- Replacing the slow techniques (TXRF, SIMS)
- B and P implants detection in gate etch
- Aerosol detection in photoresist processing
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