REAL-TIME CONTROL OF HIGH-κ DIELECTRIC THIN FILM COMPOSITION

Dong Ni, Yiming Lou, Panagiotis D. Christofides, Lin Sha, Sandy Lao, and Jane P. Chang

Department of Chemical Engineering
University of California, Los Angeles

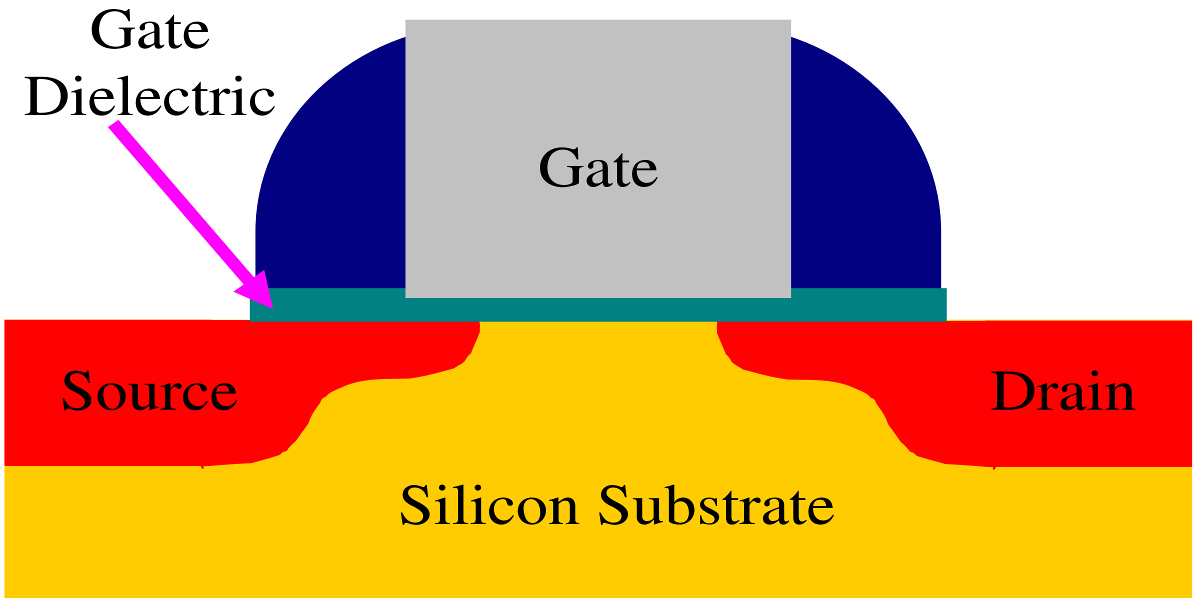
AIChE Annual Meeting
San Francisco
Nov. 17, 2003

OUTLINE

(Ni, et al., IEEE TSM, 2004)

- Introduction.
  - ◇ High-κ dielectrics.
  - ◇ Plasma-enhanced chemical vapor deposition (PECVD).
  - ◇ Process control of semiconductor device fabrication.
- Experimental setup and measurement systems.
  - ◇ Experimental PECVD system.
  - ◇ Optical emission spectroscopy (OES).
  - ◇ X-ray photoelectron spectroscopy (XPS).
- Real-time carbon content control for PECVD ZrO_2 growth.
  - ◇ Carbon content estimation and real-time feedback control.
  - ◇ Experimental results and thin film characterizations.

HIGH-κ DIELECTRICS



Cross-section drawing of a MOS transistor.

- Replace SiO_2 by high-κ materials.
  - ◇ Decrease of device dimensions.
  - ◇ High leakage current of ultra thin SiO_2 film.
  - ◇ ZrO_2 is a leading candidate to replace SiO_2.

PLASMA-ENHANCED CVD

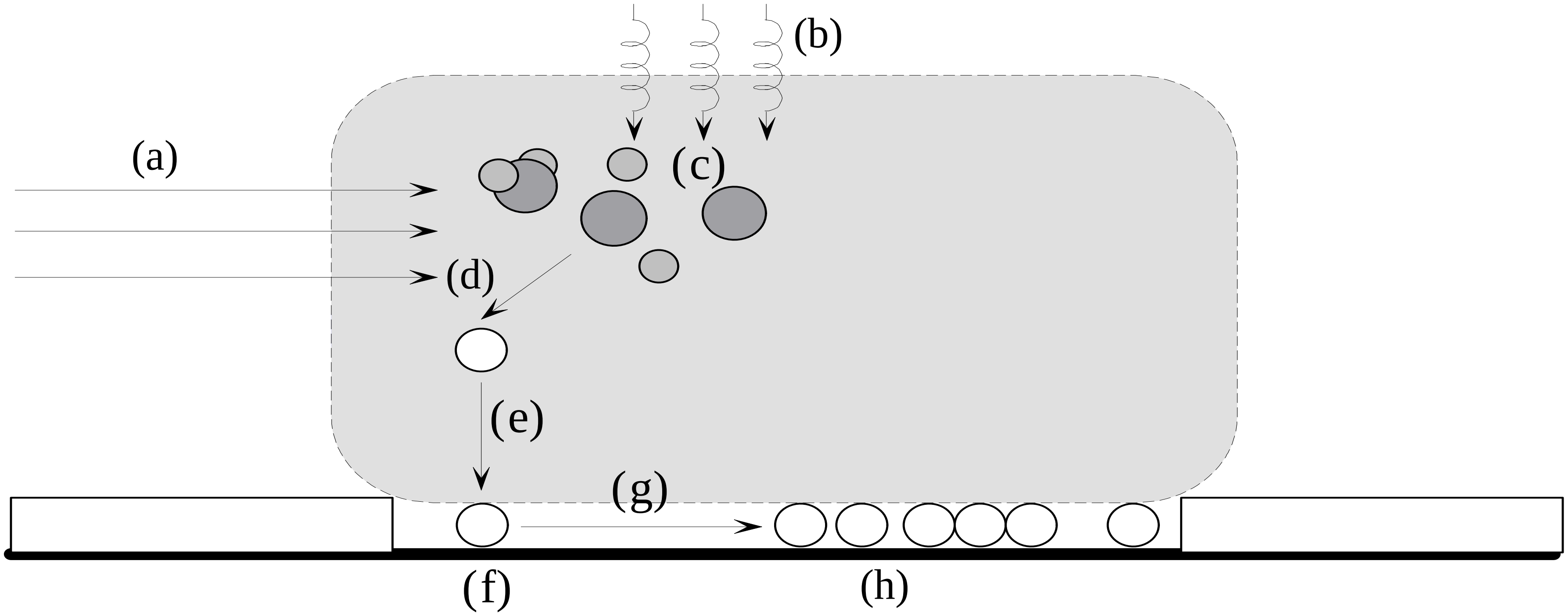


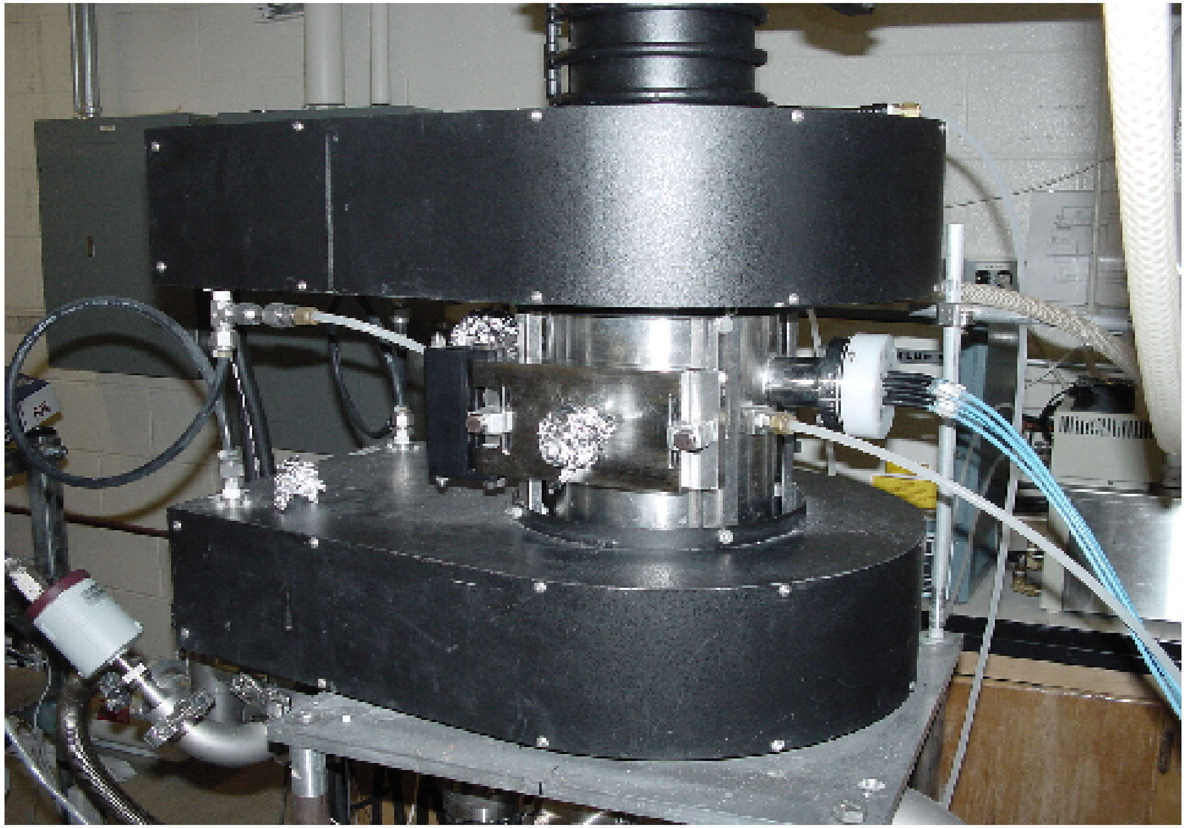
Illustration of plasma-enhanced chemical vapor deposition.

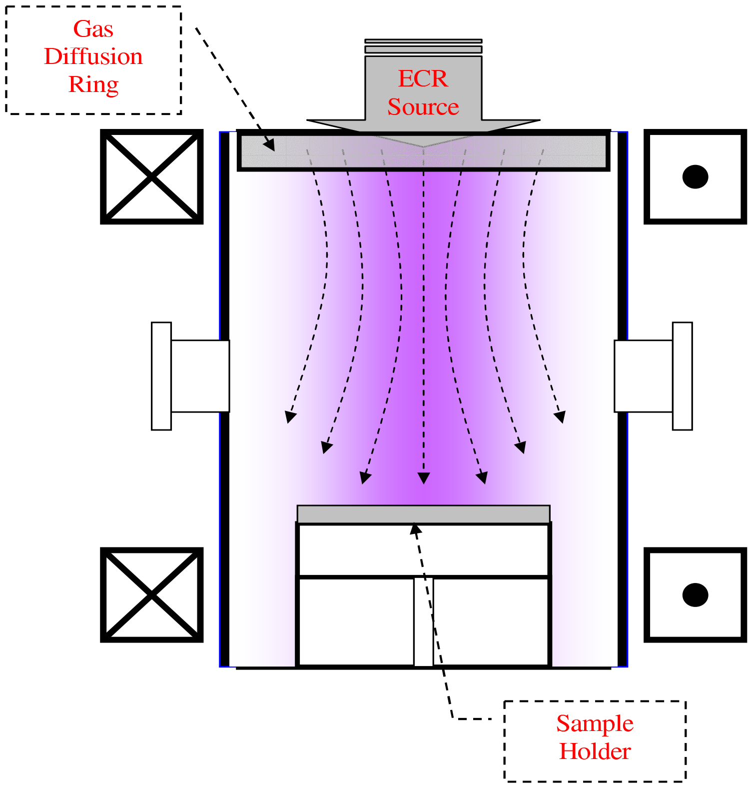
- Deposition of dielectric thin films by PECVD.
  - ◇ Higher growth rate.
  - ◇ Outstanding step coverage.
  - ◇ Lower deposition temperature compared to conventional CVD.

PROCESS CONTROL OF SEMICONDUCTOR DEVICE FAB

- Primary categories of process control in semiconductor device fabrication.
  - ◇ Plant management, contamination control, materials handling, and unit operations control (Lee 1990).
- Recipe-based open-loop unit operation.
  - ◇ Based on off-line optimization.
  - ◇ Inflexible and non-robust.
- Real-time feedback control.
  - ◇ Robust and flexible.
  - ◇ Feedback control of MOCVD growth of submicron compound semiconductor films (Warnick and Dahleh 1998).
  - ◇ Plasma enhanced chemical vapor deposition: Modeling and control of deposition spatial uniformity (Armaou and Christofides 1999).

ECR PECVD REACTOR

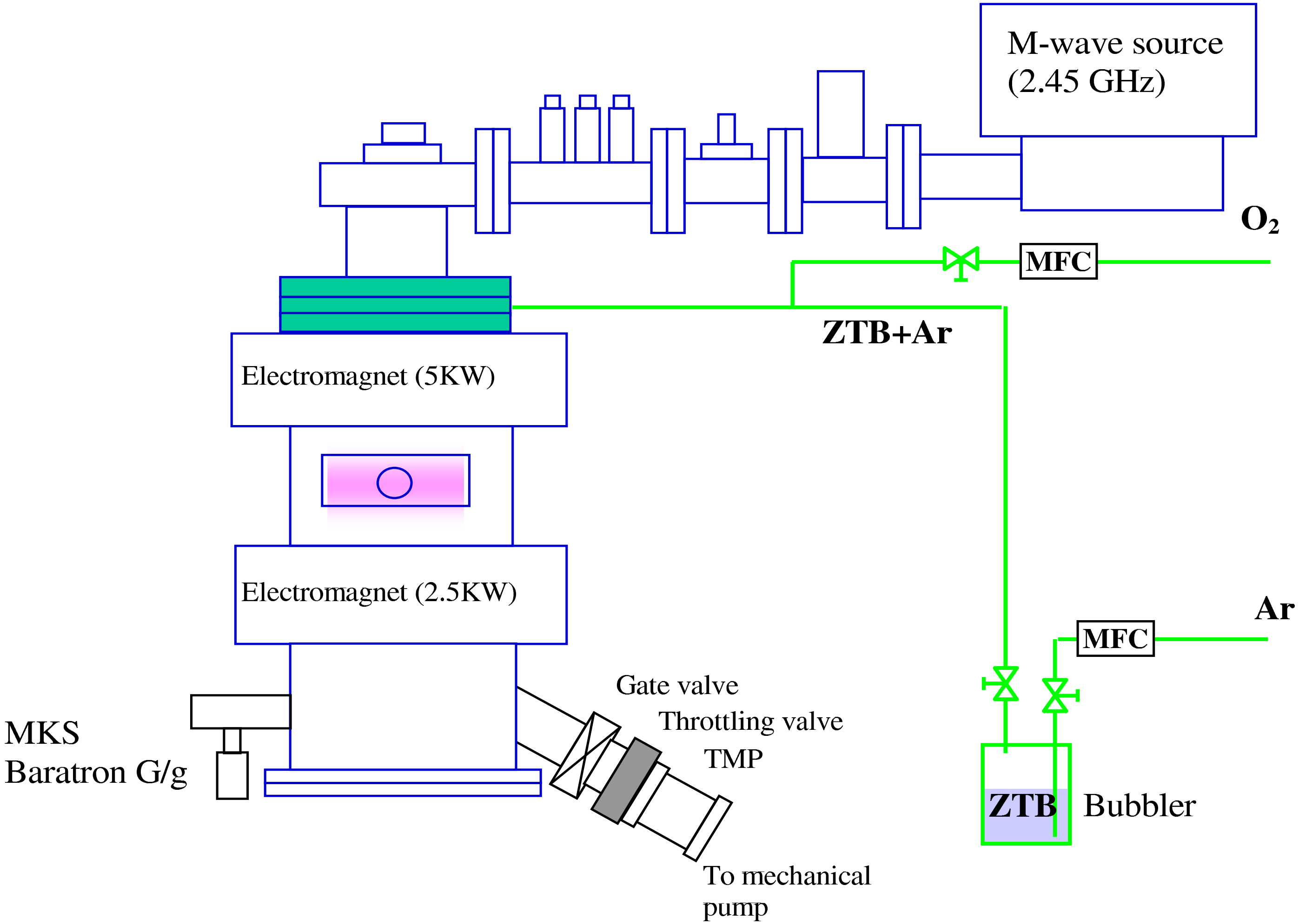




Electron cyclotron resonance (ECR) PECVD reactor.

- Experimental ECR high density PECVD reactor.
  - ◇ 6-inch stainless-steel chamber and 4-inch aluminum sample holder.
  - ◇ Optical ports are installed for plasma diagnostics.

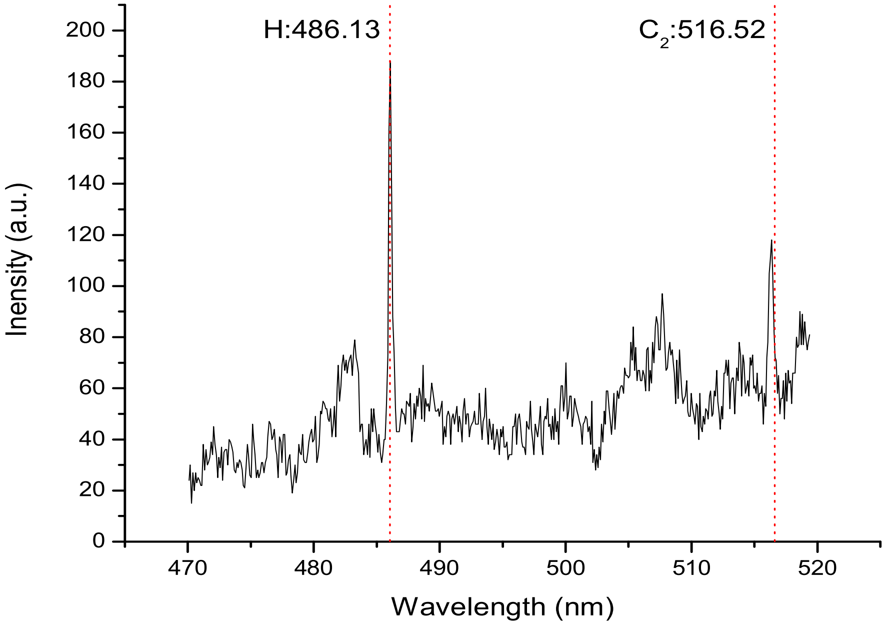
PECVD PROCESS FLOWCHART

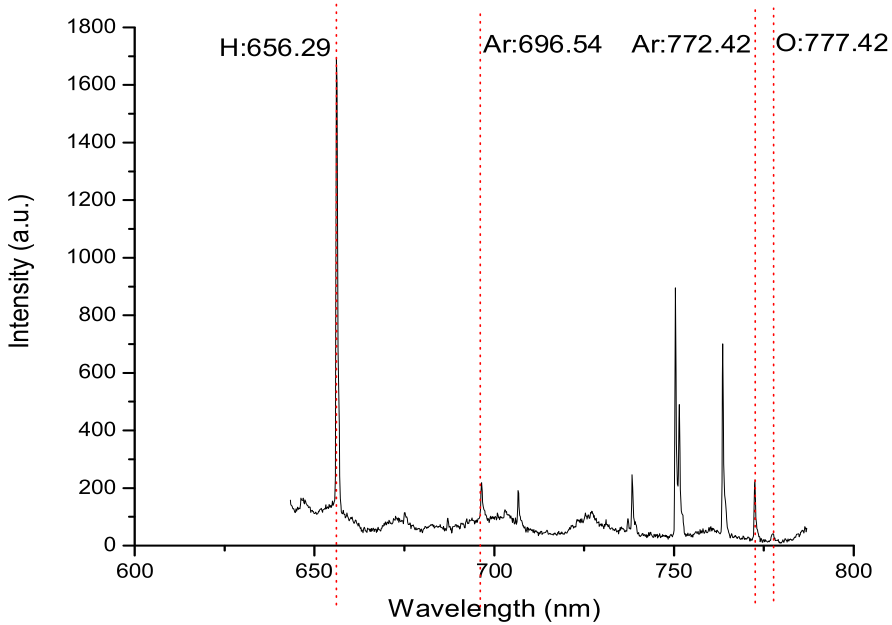


Flowchart of the experimental process system.

- Zirconium tetra-tert-butoxide $[Zr(OC_4H_9)_4]$ (ZTB) as MO precursor.
- Bubbler heated to 65^{o}C. • Ar: carrier gas. • O_2: oxidant.

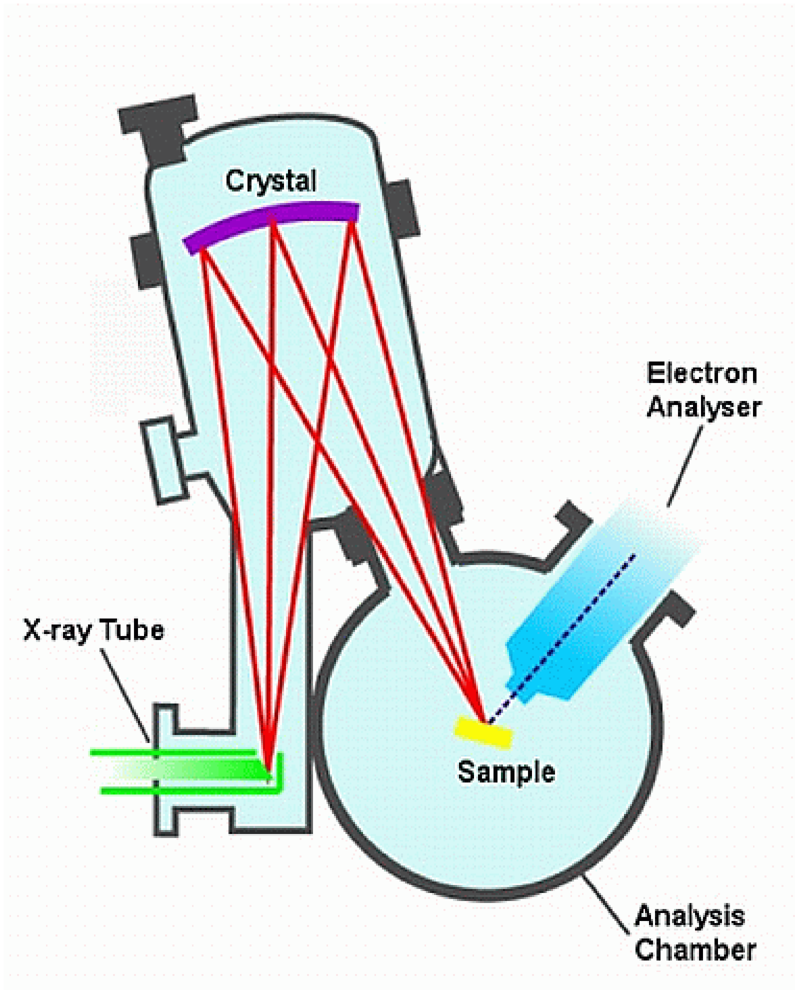
OPTICAL EMISSION SPECTROSCOPY

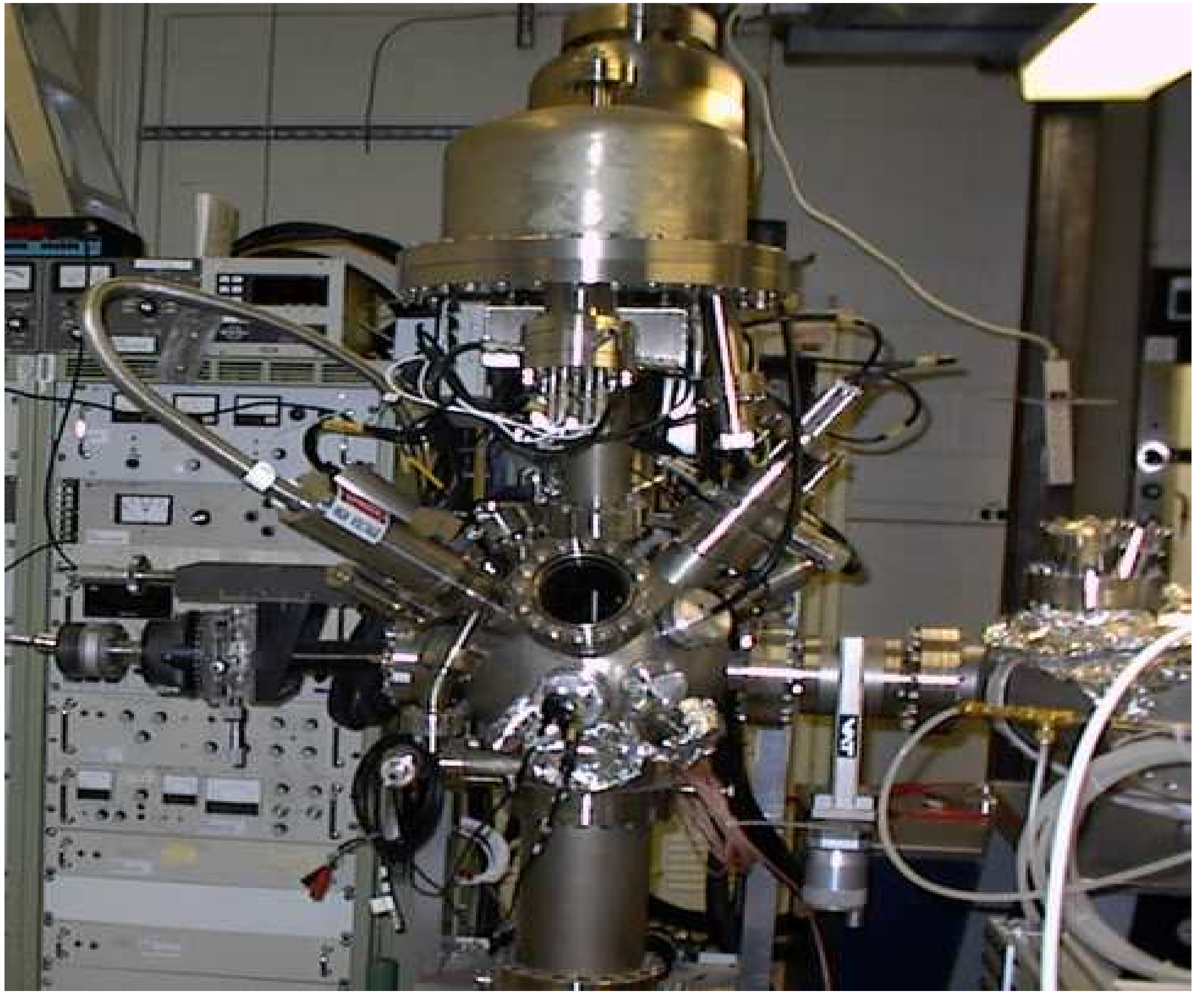




- Ocean Optics MC2000 OES system.
  - ◇ 5 channels of 2048 pixels CCD arrays.
  - ◇ Covering the wavelength range between 200 nm to 1000 nm.
  - ◇ Optical emission spectra taken at 1 inch above the wafer.

X-RAY PHOTOELECTRON SPECTROSCOPY (XPS)





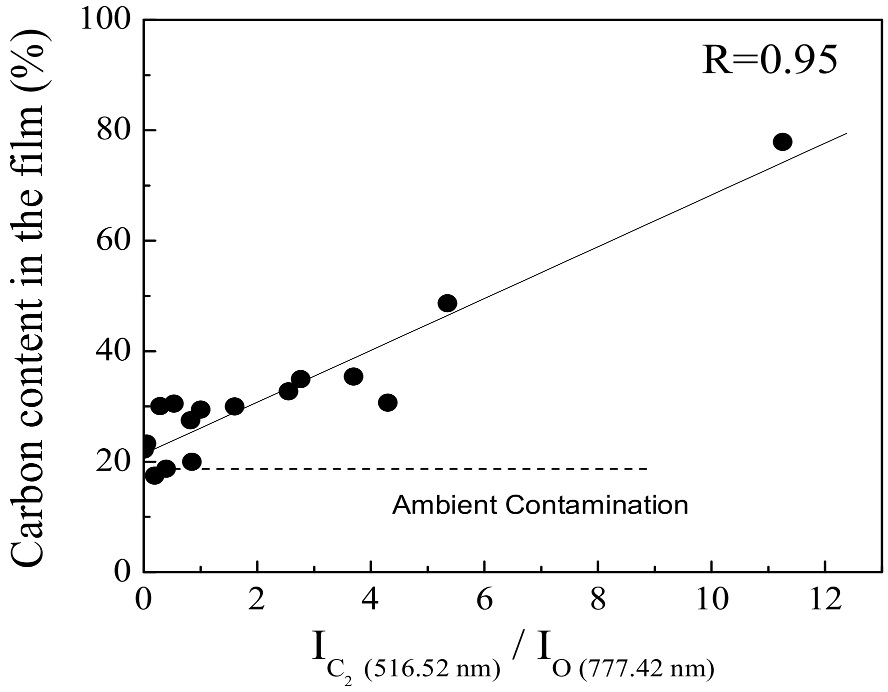
- X-ray photoelectron spectroscopy system.
  - ◇ *Al* K_α x-ray radiation source.
  - ◇ VG ESCALAB 5 electron spectrometer.
  - ◇ Surface C 1s peak at 284.6 eV as reference.

REAL-TIME FEEDBACK CARBON CONTENT CONTROL

- Control problem formulation:
  - ◇ Lower carbon content.
  - ◇ Eliminate variations of carbon content of ZrO_2 thin films.
  - ◇ Convert the batch control problem to a set-point regulation problem.
- Estimation:
  - ◇ Carbon content estimation using in-situ (real-time) OES measurements.
  - ◇ Carbon content estimator calibration using ex-situ (off-line) XPS measurements.
- Manipulated variable:
  - ◇ O_2 mass flow rate.

CARBON CONTENT ESTIMATION USING OES

- Carbon content is correlated with optical emission intensity ratio of C_2 to O (Cho et al., 2001).



- Linear regression formula:

$$\boxed{X_C^s = A\gamma}$$

CARBON CONTENT ESTIMATION USING OES

- Real-time carbon content estimation model:

$$\boxed{X_C(t) = A\frac{\int_{T_0}^{t} \gamma(s)ds}{t - T_0}}$$

- Real-time carbon content estimation model in discrete-time form:
  - Explicit expression

$$\boxed{X_C(k) = A\frac{\sum_{i=k_0}^{k} \gamma(i)}{k - k_0} \quad k > k_0}$$

  - Recursive expression

$$\boxed{X_C(k) = \frac{A}{k - k_0}\gamma(k) + [N(k-1)]\frac{k - k_0 - 1}{k - k_0} \quad k > k_0}$$

REAL-TIME CARBON CONTENT CONTROLLER

- Proportional-integral control algorithm is employed:

$$\boxed{\begin{aligned} U(t) &= K_c\hat{e}(t) + K_i \int_{t_0}^{t} \hat{e}(\mu)d\mu + \bar{R}_f \\ \hat{e}(t) &= e(t) \quad |e(t)| > \epsilon \\ &= 0 \qquad\ |e(t)| \leq \epsilon \end{aligned}}$$

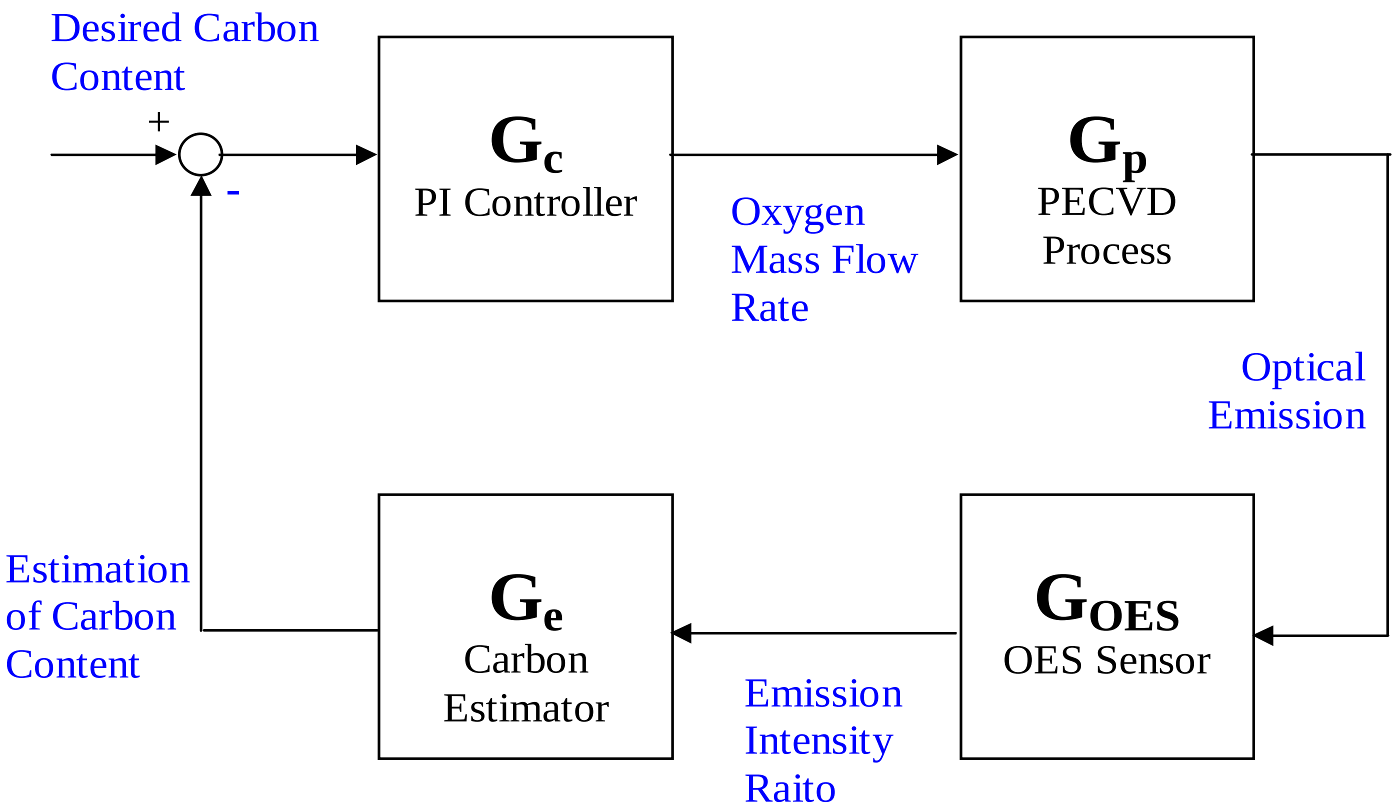
- Controller expression in discrete-time recursive form:

$$\boxed{U(k) = U(k-1) + K_c[\hat{e}(k) - \hat{e}(k-1)] + K_i T_s \hat{e}(k)}$$

- Manipulated variable: O_2 mass flow rate.

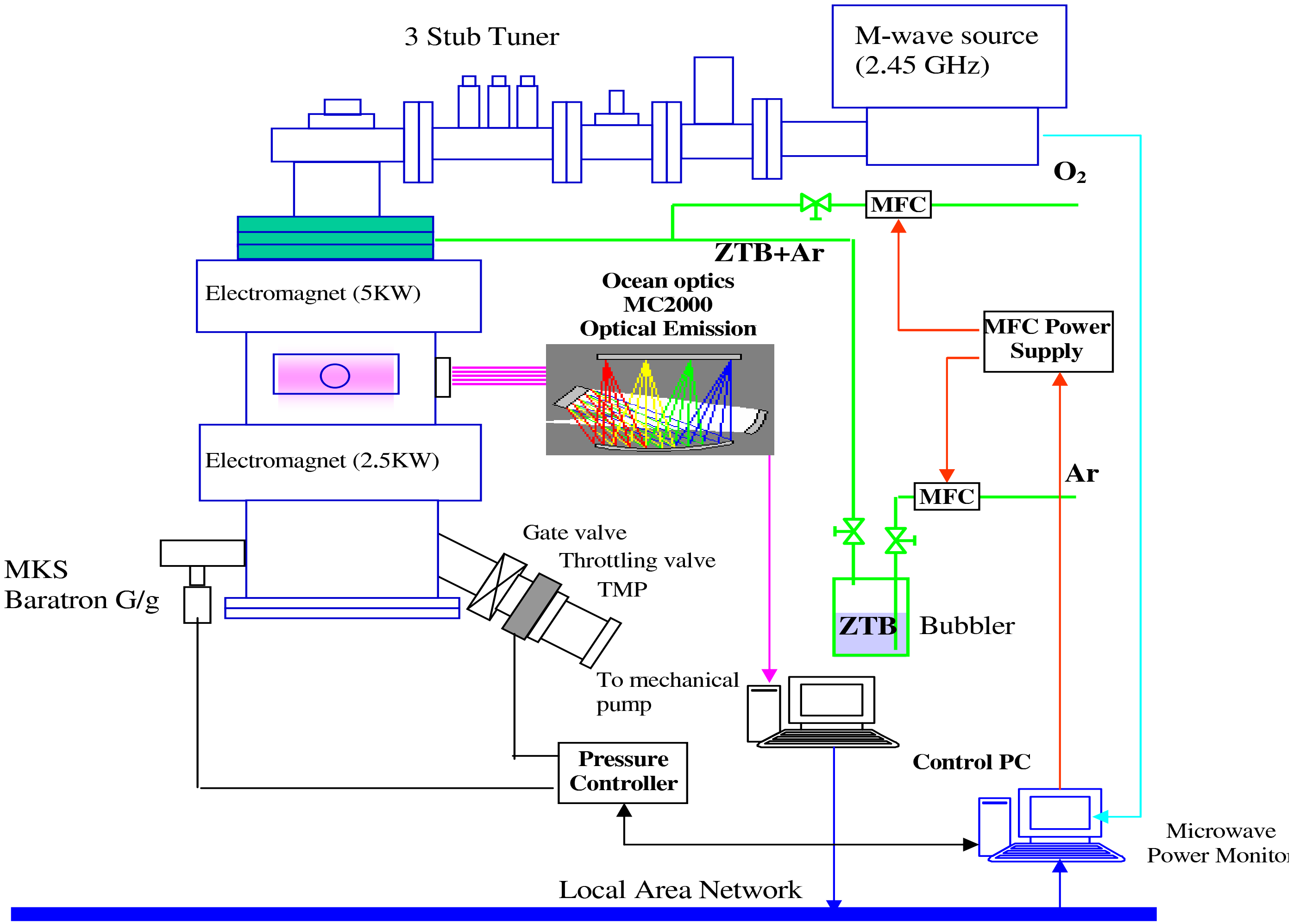
$$\boxed{f_{O_2}(k) = \frac{f_{Ar}(k)}{U(k)}}$$

REAL-TIME CARBON CONTENT CONTROL SYSTEM



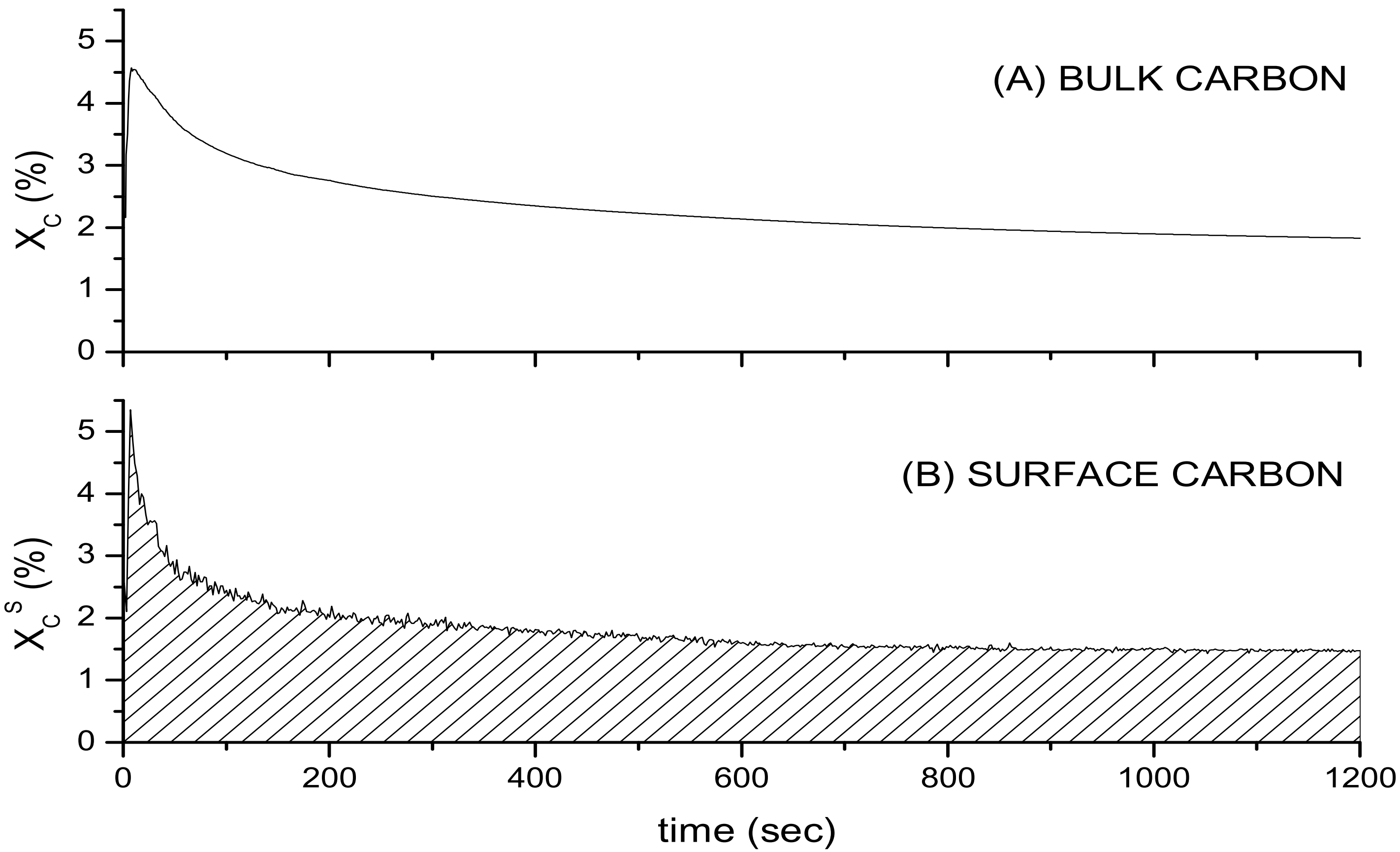
Block diagram of the closed-loop system.

COMPUTER-BASED CONTROL SYSTEM



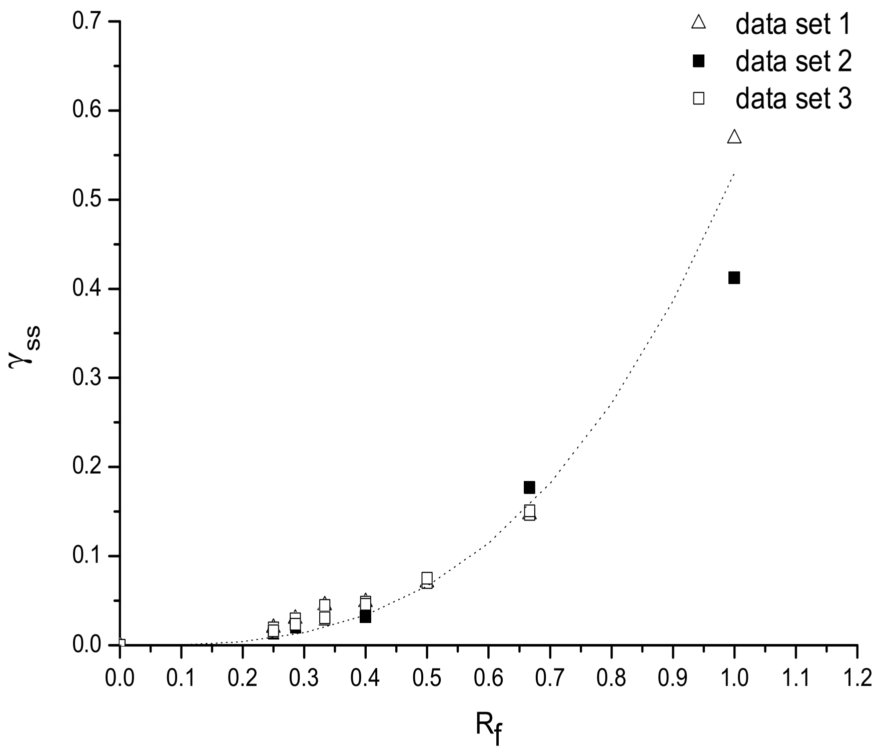
- Pentium III 700 MHz PC with 512MB RAM.
- National Instruments LabVIEW for Windows Version 6.1.
- National Instruments 16 bit DAQ boards: PCI-6034E and NI 6704.

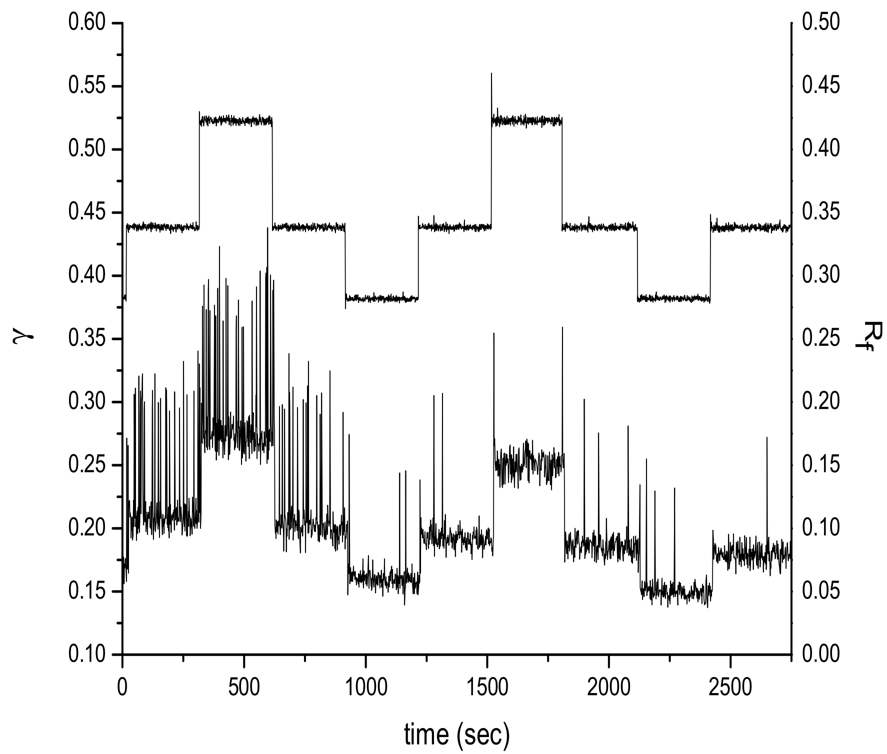
OPEN-LOOP DYNAMICS

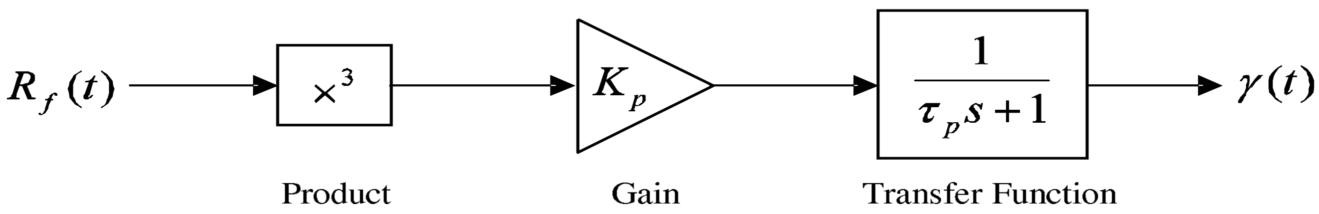


- Carbon content takes considerably long time to reach steady state.

PROCESS IDENTIFICATION

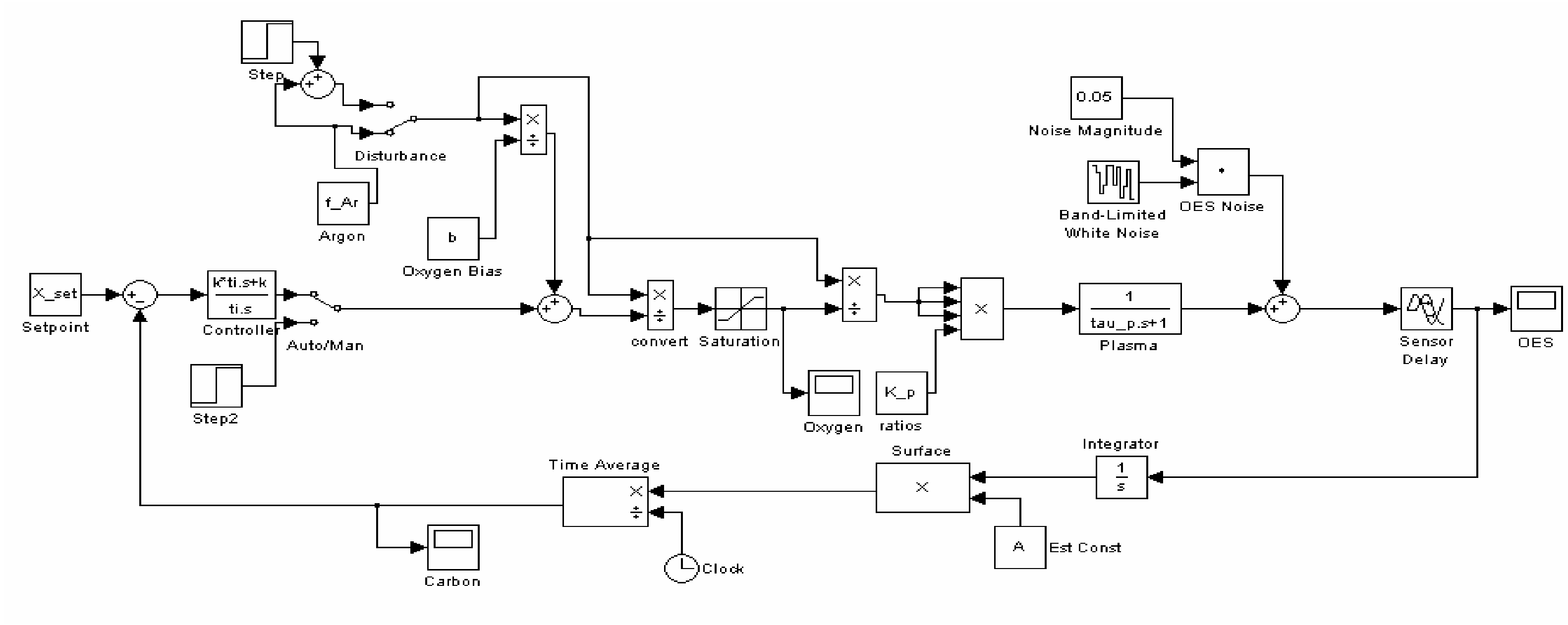


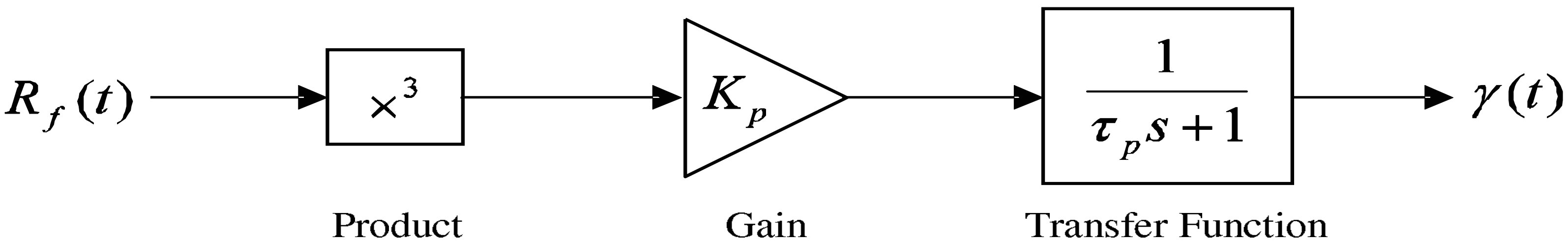




- The relationship between the steady-state of γ and R_f is almost cubic.
- The input/output dynamics can be approximated by a first-order system with a small time constant.

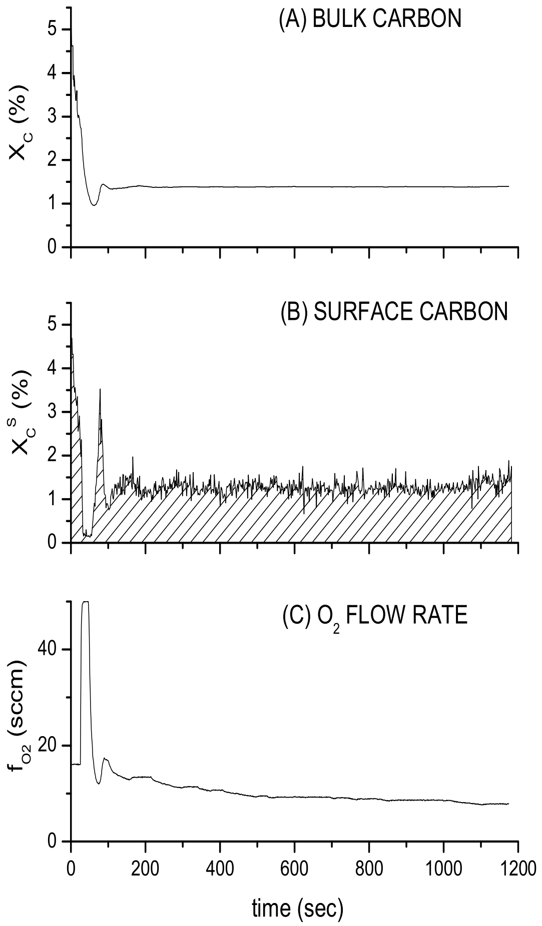
CONTROLLER TUNING

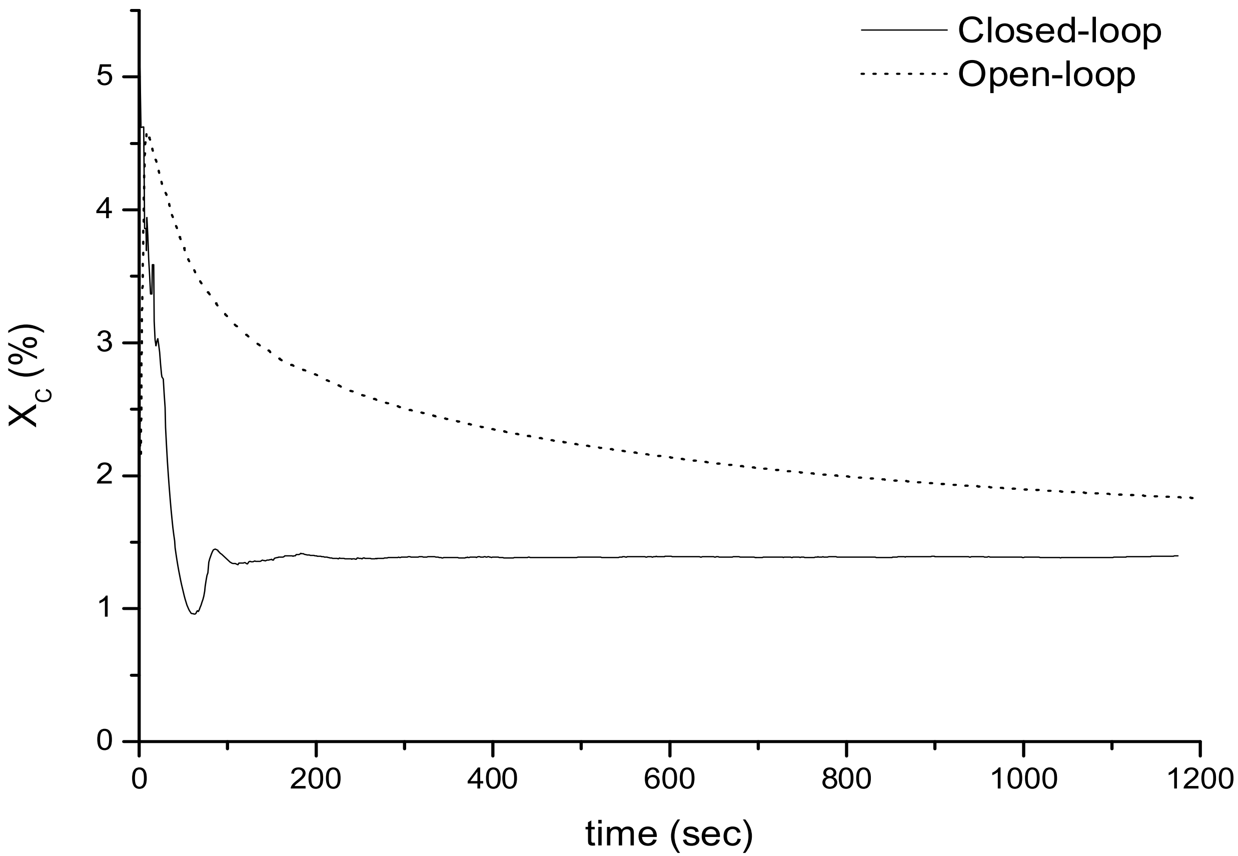




- Process system is simulated using Simulink.
- Controller is pre-tuned by simulation using Ziegler-Nichols method.
- The controller parameters are further adjusted based on the experimental conditions to achieve desired performance.

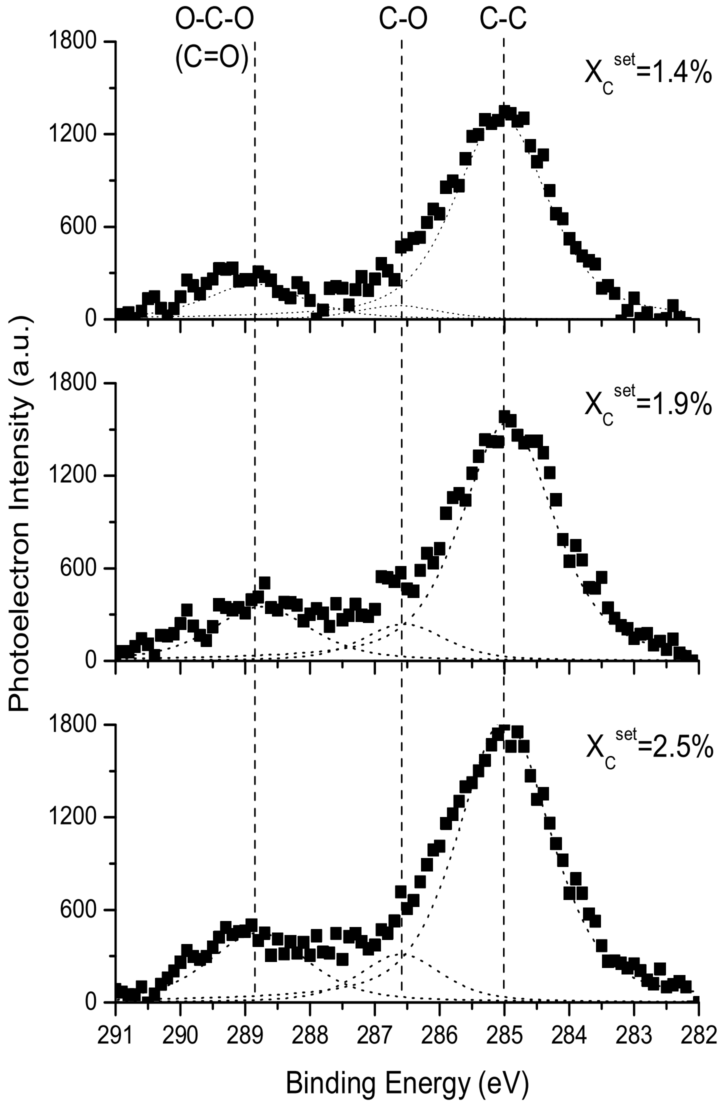
CLOSED-LOOP DYNAMICS

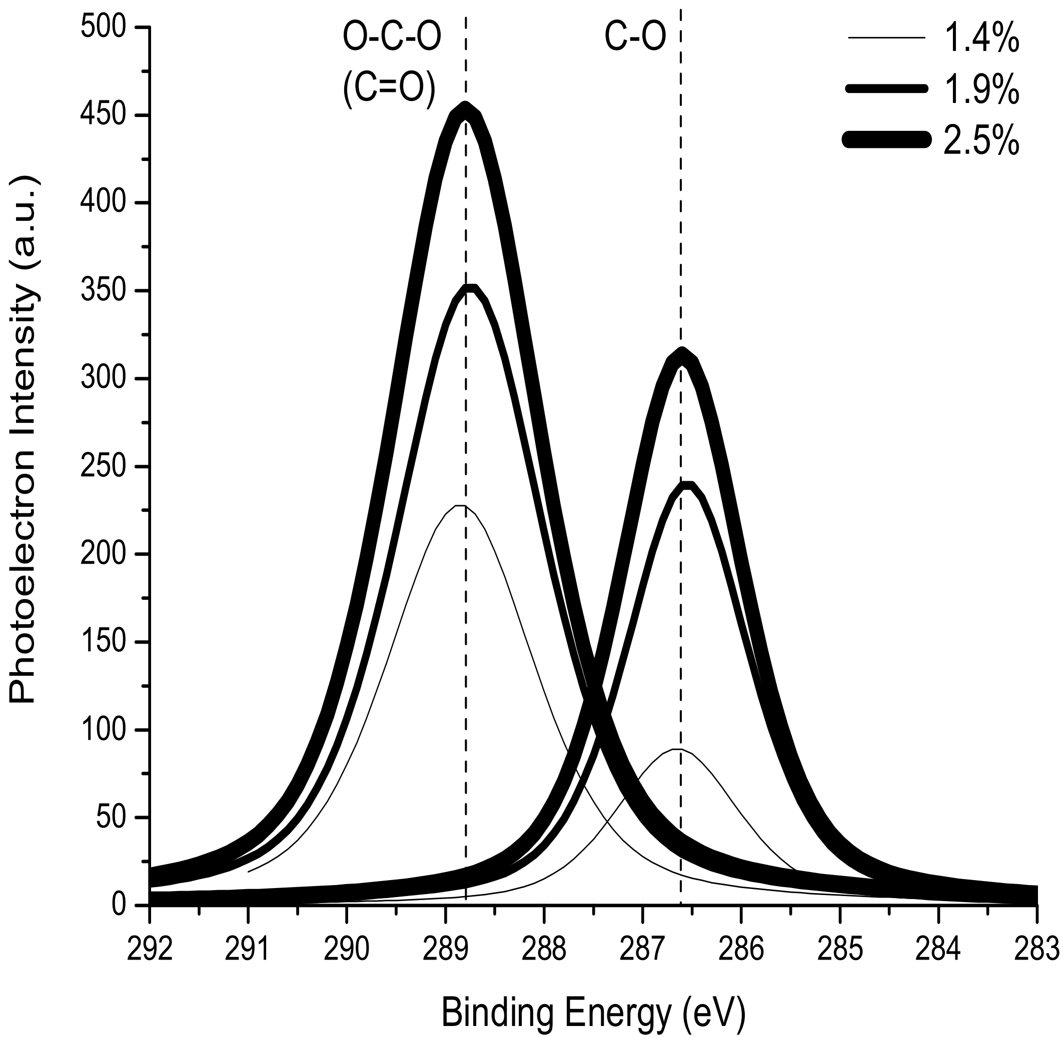




- Carbon content is controlled at desired value with little fluctuation.
- Carbon content and transition time is reduced significantly under feedback control.

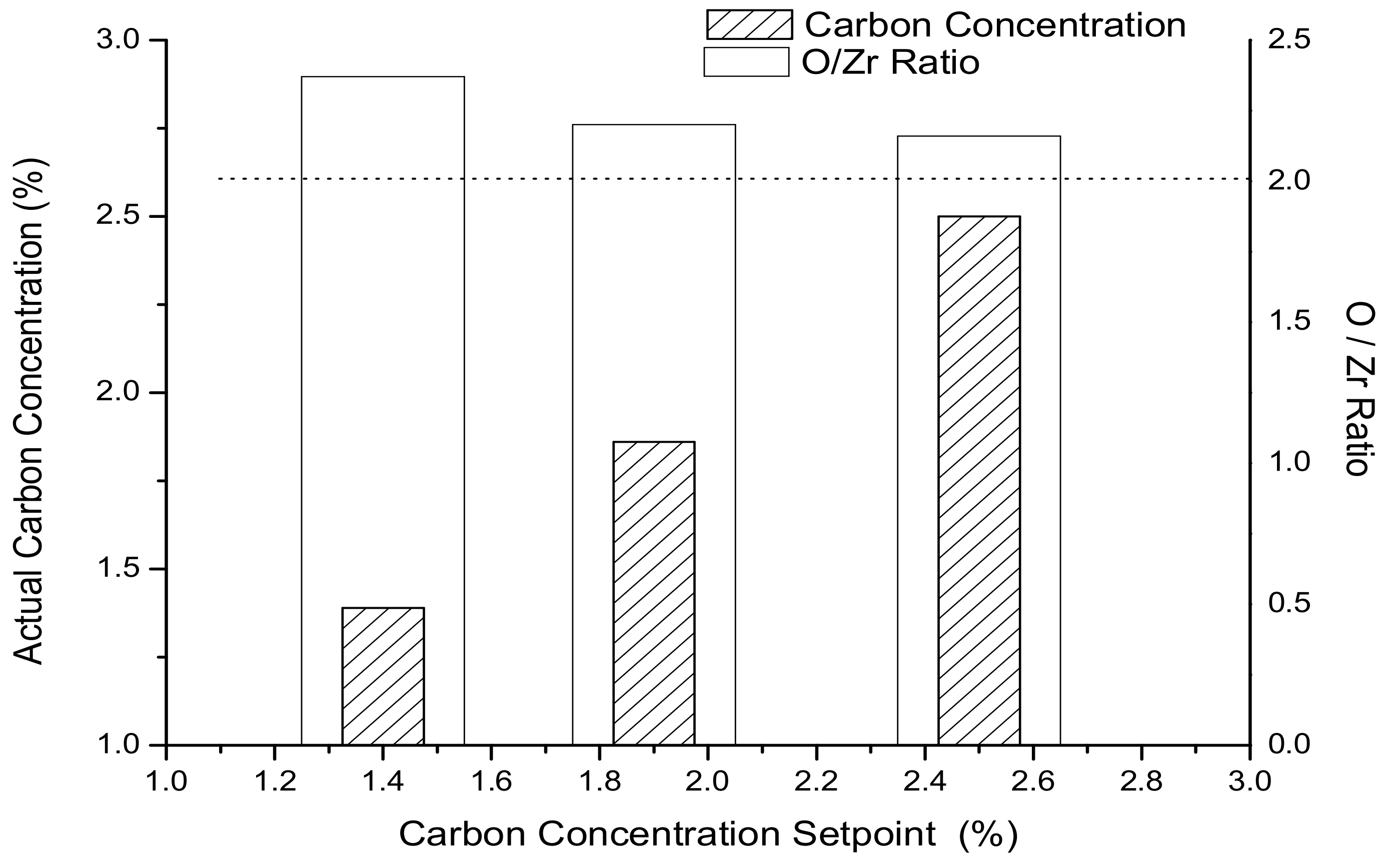
XPS ANALYSIS





- $C - C$ peaks are mostly due to the ambient contamination.
- Carbon peak area decreases consistently with decreasing set-point.

CARBON CONCENTRATION AND O/Zr RATIO



- The actual carbon concentration in the deposited films matches very well with the corresponding set-points.
- Fully stoichiometric grown ZrO_2 films are obtained by feedback-controlled depositions.

CONCLUSIONS

- Real-time feedback control of carbon content of ZrO_2 thin films.
  - ◇ Real-time carbon content estimator using optical emission intensity ratio of C_2 and O by OES.
  - ◇ Proportional-integral feedback controller.
- Implementation of real-time carbon content controller and experiments.
  - ◇ A computer-based carbon content control system is implemented on a PECVD reactor.
  - ◇ Experimental results suggest that low carbon content, small variation, and robust operation can be achieved with feedback control.
  - ◇ XPS thin film characterization verified feedback control performance.
- Combination of OES and XPS can be used to estimate other film species.

ACKNOWLEDGEMENT

- Financial support from the NSF (ITR), CTS-0325246, is gratefully acknowledged.