Spatially Programmable Reactor Design: Toward a New Paradigm for Equipment Effectiveness

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Process Realities in Semiconductor Manufacturing

Process change is ubiquitous
- Development
  - New technology nodes (roadmap)
  - Increasing demand for new, complex materials and processes
- Manufacturing
  - Tuning for process integration
  - Technology shrink

Process optimization requires tradeoffs between multiple metrics
- Materials & device performance
  - conductivity, conformality, stress, ...
- Manufacturing efficiency
  - deposition rate, uniformity, ...

MANUFACTURING EFFICIENCY
- deposition rate
- uniformity

MAT’S & DEVICE PERFORMANCE
- conductivity
- conformality
- stress
- ...

PROCESS PARAMETERS
- temperature, time, flow rates, pressure, ...
- and process recipe logic and timing

DIELECTRICS POTENTIAL SOLUTIONS

1997 NTRS

MANUFACTURING
- deposition rate
- uniformity

The Institute for Systems Research

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Two Fundamental Problems

1. Process chamber design is fixed

- Uniformity strongly influenced by (fixed) reactor design
- Process change impacts (often degrades) uniformity
- **Process optimization is constrained by fixed reactor design**

2. Experimental process studies are expensive

- Cost
  - Factory economics
- Time required
  - Time to market
- **Process optimization is costly in development and manufacturing**
Spatially Programmable Reactor Design: a New Paradigm for Equipment Effectiveness

CONCEPT

• Achieve *spatially programmable reaction rates* across the wafer
  – Spatial distributions of: CVD reactant, plasma power, CMP polish pressure, plating current, …

• Assure *across-wafer uniformity* independent of desired nominal process design point

• Use *intentional across-wafer nonuniformity* for rapid process optimization

• Exploit *sensor and control systems*

• Build upon *simulation* and reduced-order models for control
Current Practice

Design of experiments (DOE)

Evaluate performance metrics
- Material quality
- Conformality
- Other

Evaluate manufacturing metrics
- Throughput
- Across-wafer uniformity

Tradeoff analysis
- Compromise performance metrics to achieve acceptable manufacturing metrics

Uniformity

Choose compromise as process design to balance uniformity and material quality for fixed reactor configuration

Material quality
Choose process design point for optimal material and device performance

Uniformity unacceptable

Retune spatial conditions in programmable reactor

Produce high uniformity with optimal material and device performance

Programmable Uniformity to Optimize Quality & Manufacturability
Programmable CVD Reactor
Basic Design Concept

Conventional CVD reactor

Spatially Programmable CVD reactor

x,y programmable gas injection array

Heated Susceptor

Wafer

Heated Showerhead

Reactor

Gas Inlet to Showerhead

Gas Exhaust to Process Pumps
Prior Relevant Work

**Chemical Vapor Deposition**


Chemical Vapor Deposition Reactor and Method of Operation (4,993,358, 2/19/91), I. Mahawili (Watkins-Johnson)

**Plasma Processing**

Method and Apparatus for Tuning Field for Plasma Processing using Corrected Electrode (5,716,486, 2/10/98), G. S. Selwyn, M. Dalvie, C. R. Guarnieri, J. J. McGill, G. W. Rubloff, M. Surendra (IBM)

**Limited development, implementation, or use of spatially programmable / tunable reactor concepts**
Programmable CVD Reactor Design with In-Situ Sensing and Control

Multizone, distributed reactant gas inlet
- Gas flow rates and compositions controlled within each showerhead segment

Sensors embedded in the showerhead
- Spatially resolved, multizone wafer and process state measurements

Supplementary pumping through the showerhead
- Reduced inter-segment gas mixing, precise composition control, gas sampling for chemical sensing

Simulation and reduced-order models
- Support for process equipment design and control

Diagram:
- Illumination Source
- Multipoint Gas Pumping & Sensing (e.g., mass spec)
- Multipoint Optical Sensing (e.g., full-wafer interferometry)
- Multisector Gas Inlet and Showerhead
- Reactor
- Heated Susceptor
- Wafer
- Gas Exhaust to Process Pumps
Segmented Showerhead for Spatially Programmable CVD

**KEY FEATURES**

- Multizone, distributed reactant gas inlets comprise showerhead
- Inlet combined with exhaust within quasi-independent segments
- Spatially-resolved gas sensing
- Simulation and reduced-order models
- Multizone control system

**Showerhead Assembly**

Programmable Across-Wafer Uniformity
Segment Design for Spatially Programmable CVD

- Incorporate both inlets and exhaust in each segment
  - Control intra-segment uniformity
- Locate segment shields near wafer surface
  - Pump most exhaust through showerhead
  - Minimal gas transport across wafer surface beyond source segment
  - Simplify control problem associated with full-wafer radial crossflow problem of conventional designs
  - Minimize inter-segment mixing
- Adjust flow rates, spacings
  - Control across-wafer uniformity
- Extendible to even larger wafers
Showerhead Segments
Integrated Inlet and Exhaust

No inter-segment convective mixing
(cf. annular showerhead designs)

Gas is sufficiently cooled to reduce showerhead deposits.

velocity vectors

temperature
Experimental Testbed: Spatially Programmable CVD Showerhead

3-segment prototype
Exhaust and inlet in each segment
Adjustable spacings to wafer
  intersegment vs. intrasegment mixing
Extensive coupling to modeling

individual segment: quasi-independent mini-showerhead incorporating gas inlet, exhaust, sensing, and model-based control of actuation
Experimental Testbed:
Spatially Programmable CVD Showerhead

- Ulvac ERA-1000 W CVD cluster tool
- W CVD process using WF$_6$ + H$_2$
Segment – Wafer Spacing

- Si wafer
- substrate heater
- exhaust inlets

$d=1.5 \text{ mm}$

$d=3.5 \text{ mm}$
Segment – Wafer Spacing

W CVD from WF$_6$ + H$_2$
Temperature 400°C
Process time 20 min
Spacing d varied

- **Closer segment-wafer spacing reduces inter-segment mixing**
  - Ultimately the key to across-wafer uniformity control

- **At low flow rates, downstream exhaust mixing and back diffusion alters composition & deposition rates**

- Nucleation, adhesion require attention

$d = 2.5$ mm
$d = 3.5$ mm
$d = 4.5$ mm
$d = 6.5$ mm
Programmable Nonuniformity for Rapid Materials & Process Development

One-wafer DOE ➔ process optimization

Combinatorial CVD ➔ new materials discovery and development
Spatially Programmable Equipment: a New IT-Based Design Paradigm

Flexible equipment design (changeable, programmable)
Sensors, actuators, and control systems
Modeling and simulation
Enhanced optimization and development processes

Experiment

Real-time process data
Gas composition settings to each segment
Off-line metrology data

Processed experimental data
Reduced models, process recipes
Processed experimental data
Reduced models

Educational case studies: data, simulations
Off-campus databases: physical properties, chemical kinetics

Modeling, simulation, & information technology

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Conclusions

• Tradeoffs required between manufacturing requirements and technology drivers compromise both
• Spatially programmable reactor paradigm promises to decouple uniformity and material performance
• Multizone gas injection showerhead provides a means to spatially programmable CVD
• Key design element is exhaust pumping
  – through showerhead segments
  – with segment baffling close to wafer
  ➔ segments function as quasi-independent mini-showerheads
• First experimental prototype constructed; data, modeling, and analysis ongoing
• Progress contingent on substantial modeling, sensing, and control methodologies
• Promise of flexible, intelligent equipment desire is great, but numerous challenges lie ahead
Abstract

Conventional single-wafer CVD reactor designs employ showerhead gas inlets which distribute impinging gases across the wafer in an attempt to achieve across-wafer process uniformity. However, it is difficult to maintain acceptable manufacturing uniformity as process parameters are changed, or to compensate for equipment asymmetries that influence uniformity. We have developed a new approach which exploits spatial programmability of impingement gas flux and stoichiometry, using a multi-segment showerhead design that accommodates gas inlet, exhaust, and sensing in each element of a 2-D array, with two goals: (1) to achieve across-wafer uniformity at any desired process design point; and (2) to intentionally introduce across-wafer nonuniformity so as to carry out multiple experiments on a single wafer (then followed by retuning to achieve uniformity at the optimized process design point). We have constructed a three-segment prototype for initial proof-of-concept, parameter identification, and model validation. Experimental results for W CVD demonstrate both inter-segment and intra-segment deposition rate tunability, in accord with expectations from modeling and simulation. Spatially programmability of reactor design, if scalable to higher integration levels with effective sensing, actuation, and control systems, could bring forth a new paradigm in equipment design that enables rapid optimization, higher process performance at high uniformity, and design scalability to larger substrates and multiple technology generations.