PLASMA ATOMIC LAYER ETCHING USING CONVENTIONAL PLASMA EQUIPMENT*

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AGENDA

- Atomic Layer Processing
- Plasma Atomic Layer Etching (PALE)
- Approach and Methodology
- Demonstration Systems
- Results
  - PALE of Si using Ar/Cl₂
  - PALE of SiO₂ using Ar/c-C₄F₈
  - PALE of Self-aligned contacts
- Concluding Remarks
• Gate-oxide thickness of only a few monolayers are required for the 65 nm node.

• 32 nm node processes will require control of etching processes at the atomic scale.


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ATOMIC LAYER PROCESSING

- Advanced structures (multiple gate MOSFETs) require extreme selectivity in etching different materials.
- Atomic layer processing may allow for this level of control.
- The high cost of atomic layer processing challenges its use.
- In this talk, we discuss strategies for Atomic Layer Etching using conventional plasma processing equipment.
- Lower cost, equipment already in fabs.

Refs: AIST, Japan; Intel Corporation

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PLASMA ATOMIC LAYER ETCHING (PALE)

- In PALE etching proceeds monolayer by monolayer in a cyclic, self limiting process.
  - In first step, top monolayer is passivated in non-etching plasma.
  - Passivation makes top layer more easily etched compared to sub-layers.
  - Second step removes top layer (self limiting).
  - Exceeding threshold energy results in etching beyond top layer.

Diagram:
- Step 1:
  - Passivate
  - Ions, Neutrals
  - Passivation Layer
  - Repeat
- Step 2:
  - Etch ($\varepsilon < \varepsilon_{th}$)
  - Ions
  - Etch ($\varepsilon > \varepsilon_{th}$)
  - Surface
DEMONSTRATION OF PALE

- Repeatability and self-limiting nature of PALE has been demonstrated in GaAs and Si devices.
- Commercially viable Si PALE at nm scale not yet available.

HYBRID PLASMA EQUIPMENT MODEL (HPEM)

- Electromagnetics Module: Antenna generated electric and magnetic fields
- Electron Energy Transport Module: Beam and bulk generated sources and transport coefficients.
- Fluid Kinetics Module: Electron and Heavy Particle Transport, Poisson’s equation
- Plasma Chemistry Monte Carlo Module:
  - Ion and Neutral Energy and Angular Distributions
  - Fluxes for feature profile model
MONTE CARLO FEATURE PROFILE MODEL

- Monte Carlo techniques address plasma surface interactions and evolution of surface morphology and profiles.

- Inputs:
  - Initial material mesh
  - Surface reaction mechanism
  - Ion and neutral energy and angular distributions
  - Fluxes at selected wafer locations.

- Fluxes and distributions from equipment scale model (HPEM)
PALE OF Si IN Ar/Cl₂

- Proof of principal cases were investigate using HPEM and MCFPM.
- Inductively coupled Plasma (ICP) with rf substrate bias.
- Node feature geometries investigated:
  - Si-FinFET
  - Si over SiO₂ (conventional)
**Ar/Cl₂ PALE: ION DENSITIES**

- Inductively coupled plasma (ICP) with rf bias.
- **Step 1:** Passivate
  - Ar/Cl₂=80/20, 20 mT, 500 W, 0 V
- **Step 2:** Etch
  - Ar, 16 mTorr, 500 W, 100 V

**Diagram:***
- Total Ion Density [max = 9.3 x 10¹¹ cm⁻³]
- Ar⁺ Density [max = 8.8 x 10¹¹ cm⁻³]

**Legend:**
- 0.01
- 1.0

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Ar/Cl\textsubscript{2} PALE: ION FLUXES

- Ion fluxes:
  - Step 1: Cl\textsuperscript{+}, Ar\textsuperscript{+}, Cl\textsubscript{2}\textsuperscript{+}
  - Step 2: Ar\textsuperscript{+}

- Cl\textsuperscript{+} is the major ion in Step 1 due to Cl\textsubscript{2} dissociation.

- Lack of competing processes increases flux of Ar\textsuperscript{+} in Step 2.

- Step 1: Ar/Cl\textsubscript{2}=80/20, 20 mT, 0 V
- Step 2: Ar, 16 mTorr, 100 V
Ar/Cl\textsubscript{2} PALE: ION ENERGY ANGULAR DISTRIBUTION

- PALE of Si using ICP Ar/Cl\textsubscript{2} with bias.
- Step 1
  - Ar/Cl\textsubscript{2}=80/20, 20 mTorr, 0 V, 500 W
  - Passivate single layer with SiCl\textsubscript{x}
  - Low ion energies to reduce etching.
- Step 2
  - Ar, 16 mTorr, 100 V, 500 W
  - Chemically sputter SiCl\textsubscript{x} layer.
  - Moderate ion energies to activate etch but not physically sputter.
- IEADs for all ions
  - Step 1: Ar\textsuperscript{+}, Cl\textsuperscript{+}, Cl\textsubscript{2}\textsuperscript{+}
  - Step 2: Ar\textsuperscript{+}
1-CYCLE OF Ar/Cl\textsubscript{2} PALE : Si-FinFET

- Step 1: Passivation of Si with SiCl\textsubscript{x} (Ar/Cl\textsubscript{2} chemistry)
- Step 2: Etching of SiCl\textsubscript{x} (Ar only chemistry)
- Note the depletion of Si layer in both axial and radial directions.
- Additional cycles remove additional layers.
Multiple cycles etch away one layer at a time on side.
Self-terminating process established.
Some etching occurs on top during passivation emphasizing need to control length of exposure and ion energy.
• Optimum process will balance speed of conventional cw etch with slower selectivity of PALE.

• To achieve extreme selectivity (“soft landing”) cw etch must leave many monolayers.

• Too many monolayers for PALE slows process.

• In this example, some damage occurs to underlying SiO$_2$.

• Control of angular distribution will enhance selectivity.

Aspect Ratio = 1:5
PALE OF SiO$_2$ IN Ar/c-$C_4F_8$

- Etching of SiO$_2$ in fluorocarbon gas mixtures proceeds through $C_xF_y$ passivation layer.

- Control of thickness of $C_xF_y$ layer and energy of ions enables PALE processing.

Diagram showing the etching process and the formation of a trench.
Ar/c-C₄F₈ PALE: ION DENSITIES

- MERIE reactor with magnetic field used for investigation.
- Ion energy is controlled with bias and magnetic field.
- Step 1:  
  Ar/C₄F₈=75/25, 40 mT, 500 W, 250 G
- Step 2:  
  Ar, 40 mTorr, 100 W, 0 G

• Step 1: Passivate

• Step 2: Etch
Ar/c-C₄F₈ PALE: ION ENERGY ANGULAR DISTRIBUTION

- PALE of SiO₂ using CCP Ar/C₄F₈ with variable bias.

**Step 1**
- Ar/C₄F₈=75/25, 40 mTorr, 500 W, 250 G
- Passivate single layer with SiO₂CₓFᵧ
- Low ion energies to reduce etching.

**Step 2**
- Ar, 40 mTorr, 100 W, 0 G
- Etch/Sputter SiO₂CₓFᵧ layer.
- Moderate ion energies to activate etch but not physically sputter.

**Process times**
- Step 1: 0.5 s
- Step 2: 19.5 s
SiO$_2$ OVER Si PALE USING Ar/C$_4$F$_8$-Ar CYCLES

- 20 cycles
- 1 cell = 3 Å

- PALE using Ar/C$_4$F$_8$ plasma must address more polymerizing environment (note thick passivation on side walls).

- Some lateral etching occurs (control of angular IED important)

- Etch products redeposit on side-wall near bottom of trench.
Increasing ion energy produces transition from chemical etching to physical sputtering.

Surface roughness increases when sputtering begins.

Emphasizes the need to control ion energy and exposure time.
SiO$_2$/Si TRENCH: ETCH RATE vs. ION ENERGY

- Step 1 process time changed from 0.5 s to 1 s.
- By increasing length of Step 1 (passivation) more polymer is deposited thereby increasing Step 2 (etching) process time.
- At low energies uniform removal. At high energies more monolayers are etched with increase in roughness.
• Extreme selectivity of PALE helps realize etching of self-aligned contacts.
• Some damage occurs to the “step” and underlying Si;
  • Important to control ion energies
CONCLUDING REMARKS

- Atomic layer control of etch processes will be critical for 32 nm node devices.

- PALE using conventional plasma equipment makes for an more economic processes.

- Proof of principle calculations demonstrate Si-FinFET and Si/SiO₂ deep trenches can be atomically etched in self-terminating Ar/Cl₂ mixtures.

- SiO₂/Si deep trenches can be atomically etched in self-terminating Ar/C₄F₈ mixtures.

- Control of angular distribution is critical to removing redeposited etch products on sidewalls.

- Passivation step may induce unwanted etching:
  - Control length of exposure
  - Control ion energy

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