Dry Etching Overview

- What is dry etching?
  - Material removal reactions occur in the gas phase.
- Types of dry etching
  - Non-plasma based dry etching
  - Plasma based dry etching
- Why dry etching?
  - Development of dry etching
  - Plasma parameters/influences
  - Deep Reactive Ion Etching

Dry Etching Advantages

- Eliminates handling of dangerous acids and solvents
- Uses small amounts of chemicals
- Isotropic or anisotropic etch profiles
- Directional etching without using the crystal orientation of Si
- Faithfully transfer lithographically defined photoresist patterns into underlying layers
- High resolution and cleanliness
- Less undercutting
- No unintentional prolongation of etching
- Better process control
- Ease of automation (e.g., cassette loading)

Dry Etching

- Disadvantages:
  - Some gases are quite toxic and corrosive
  - Re-deposition of non-volatile compounds
  - Need for specialized (expensive) equipment
- Types:
  - Non-plasma based = uses spontaneous reaction of appropriate reactive gas mixture
  - Plasma based = uses radio frequency (RF) power to drive chemical reaction

Non-plasma Based Dry Etching

- Isotropic etching of Si
- Typically fluorine-containing gases (fluorides or interhalogens) that readily etch Si
- High selectivity to masking layers
- No need for plasma processing equipment
- Highly controllable via temperature and partial pressure of reactants

Xenon Difluoride (XeF₂) Etching

- Isotropic etching of Si
- High selectivity for Al, SiO₂, Si₃N₄, PR, PSG
- 2XeF₂ + Si \rightarrow 2Xe + SiF₄
- Typical etch rates of 1 to 3 µm/min
- Heat is generated during exothermic reaction
- XeF₂ reacts with water (or vapor) to form HF
**Interhalogen (BrF₃ & ClF₃) Etching**
- Nearly isotropic profile
- Gases react with Si to form SiF₄
- Surface roughness: ~40 to 150 nm
- Masks: SiO₂, Si₃N₄, PR, Al, Cu, Au, and Ni

**Plasma Based Dry Etching**
- RF power is used to drive chemical reactions
- Plasma takes place at elevated temperatures or very reactive chemicals
- Types:
  - Physical etching
  - Chemical etching
  - Reactive ion etching (RIE)
  - Deep reactive ion etching (DRIE)

**Plasma**
- Plasma = partially ionized gas consisting of equal numbers of “+” (ions) and “-” (electrons) charges and a different number of neutral (un-ionized) molecules
- An ion-electron pair is continuously created by ionization and destroyed by recombination
- Typical kinetic energy (KE) of an electron in plasma is 2-8 eV
  \[ KE = \frac{1}{2} m V^2 = \frac{1}{2} kT \]

2 eV electron has
- \( T \approx 15,000 \) K
- \( V \approx 6 \times 10^7 \) cm/s
  = 1,342,16176 mph

**Plasma Formation**
- Chamber is evacuated
- Chamber is filled with gas(es)
- RF energy is applied to a pair of electrodes
- Applied energy accelerates electrons increasing kinetic energy
- Electrons collide with neutral gas molecules, forming ions and more electrons
- Steady state is reached (plasma); ionization = recombination
- Maintained at 1 Pa (75 mtorr) to 750 Pa (56 torr) with gas density of 27 x 10¹⁴ to 2 x 10¹⁷ molecules/cm³

**Plasma Parameters**
- Temperature
  - Etching rate
  - Spontaneous chemical reaction
  - Etching directivity
- Pressure
  - Ion density
  - Ion directivity
- Power
  - Ion density
  - Ion kinetic energy
- Other variables
  - Gas flow rate
  - Reactor materials
  - Reactor cleanliness
  - Loading (microlading)
  - Mask materials
Physical Etching (Sputter Etching)
- Based on physical bombardment with ions or atoms
- Plasma is used to energize a chemically inert projectile so that it moves at high velocity when it strikes the substrate
- Momentum is transferred during the collision
- Substrate atoms are dislodged if projectile energy exceeds bonding energy
- Very similar to ion implantation, but low-energy ions are used to avoid implantation damage
- Highly anisotropic
- Etch rates for most materials are comparable (i.e., no masking)
- Argon is the most commonly used ion source
- May result in re-deposition

Chemical (Plasma) Etching:
- Plasma is used to produce chemically reactive species (atoms, radicals, and ions) from inert molecular gas
- Six major steps:
  - Generation of reactive species (e.g., free radicals)
  - Diffusion to surface
  - Adsorption on surface
  - Chemical reaction
  - Desorption of by-products
  - Diffusion into bulk gas
- Production of gaseous by-products is extremely important

Plasma Etching Systems
- Plasma Etching (PE)
- Barrel, barrel with downstream and symmetrical parallel plate system
- Pure chemical etching
- Isotropic etching

Two Basic Plasma Systems

Reactive Ion Etching (RIE)
- RIE = process in which chemical etching is accompanied by ionic bombardment (i.e., ion-assisted etching)
- Bombardment opens areas for reactions
- Ionic bombardment:
  - No undercutting since side-walls are not exposed
  - Greatly increased etch rate
  - Structural degradation
  - Lower selectivity
**RIE System**
- Reactive Ion Etching (RIE)
- Asymmetrical parallel plate system
- Plasma, sheath and boundary layer
- Combination of physical and chemical etching
- Anisotropic etching

**Disadvantages of RIE**
- Conflict between etching rate and anisotropic profile
  - Etching rate (+) → Reactive species concentration (+) → Gas pressure (+) → Collision (+) → Anisotropic (-)
- Conflict between damage of high etching rate and anisotropic profile
  - KE (+) → Etching rate (+) → damage (+)

**Deep Reactive Ion Etching (DRIE)**
- Uses electron cyclotron resonance (ECR) source to supplement RIE system
- Microwave power at 245 GHz is coupled into ECR
- Magnetic field is used to enhance transfer of microwave energy to resonating electrons
- DRIE uses lower energy ions → less damage and higher selectivity
- Plasma maintained at 0.5 to 3 mtorr

**ECR Systems**
- Electron Cyclotron Resonance (ECR)
- Higher plasma density at lower pressure
- Control the density of the reactive ions and their kinetic energy separately
- Downstream of plasma further limits the exposure to reduce damage

**ICP System (DRIE)**
- Inductively Coupled Plasma (ICP)
- Simple system
- Almost same process result as that from the ECR system
- Two RF power generators to control ion energy and ion density separately

**Deep Reactive Ion Etching**
- high density ICP plasma
- high aspect ratio Si structures
- cost: $500K
- vendors: STS, Alcatel, PlasmaTherm

Source: LucasNova
Source: AMMISource: STS
Source: AMM
Etch Chemistries

- Organic Films
  - Oxygen plasma is required
  - By-products: CO, CO₂, H₂O
  - Masks: Si, SiO₂, Al, or Ti
  - Addition of fluorine containing gases significantly increases etch rate but decreases selectivity (due to HF formation)

- Oxide and Nitride Films
  - Fluorine plasma is required (e.g., CF₄)
  - Mask: PR
  - Addition of O₂
    - Increases etch rate
    - Adjusts PR : oxide and PR : nitride selectivity

- Silicon
  - Fluorine plasma (CF₄ or SF₆)
  - Chlorine plasma (Cl₂)
  - Mixed (fluorine and chlorine) plasma (Cl₂ + SF₆)

Process-ICP (ALCATEL)

1-High Etch Rate

Ultra- High Etch Rate Process

- Silicon
  - Fluorine plasma (CF₄ or SF₆)
  - Chlorine plasma (Cl₂)
  - Mixed (fluorine and chlorine) plasma (Cl₂ + SF₆)

Process-ICP

2-High Aspect Ratio

Ultra- High Etch Rate Process

- Silicon
  - Fluorine plasma (CF₄ or SF₆)
  - Chlorine plasma (Cl₂)
  - Mixed (fluorine and chlorine) plasma (Cl₂ + SF₆)
High Aspect Ratio

- **Wafer diameter**: 100 mm
- **Feature width**: 3.5 µm
- **Etch depth**: 85 µm
- **Etch time**: 30 min
- **Mask**: Oxide
- **Si etch rate**: 2.8 µm/min
- **Mask selectivity**: > 200 : 1
- **Uniformity**: < ± 5 %
- **Profile**: 89 Degrees
- **Undercut**: 0.3 µm
- **Process regime**: Room Temp

High Aspect Ratio Trench Etch

- **Wafer size**: 100 mm
- **Trench width**: 2 µm
- **Etch depth**: 90 µm
- **Aspect ratio**: 90 : 1
- **Etch time**: 40 min
- **Mask**: Photoresist
- **Si etch rate**: 1.6 µm/min
- **Mask selectivity**: > 100 : 1
- **Profile**: 89-90 Degrees
- **Process regime**: Room Temp

Process-ICP

3-Through the Wafer

Bulk Micromachined Spring (Through-the-wafer etch)

- **Wafer size**: 100 mm
- **Etch depth**: 400 µm
- **Mask**: Oxide
- **Si etch rate**: 3.7 µm/min
- **Mask selectivity**: > 400 : 1
- **Profile**: 90±2
- **Process regime**: Low Temp

Micro-Gears as Micro-Mechanical Components

- **Wafer size**: 100 mm
- **Etch depth**: 900 µm
- **Mask**: Oxide
- **Si etch rate**: 3.7 µm/min
- **Mask selectivity**: > 800 : 1
- **Profile**: 90±2
- **Process regime**: Room Temp

Courtesy: Case Western Reserve University

Bulk Micromachined Spring (Through-the-wafer etch)

Courtesy: Case Western Reserve University
Process-ICP

4-Variouis SOI Tapered Isotropic Etch

SOI etch with different feature sizes

<table>
<thead>
<tr>
<th>Feature with Etch depth</th>
<th>20 µm deep</th>
<th>30 µm deep</th>
<th>40 µm deep</th>
<th>50 µm deep</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si etch rate</td>
<td>3 µm/min</td>
<td>3.5 µm/min</td>
<td>4 µm/min</td>
<td>4.3 µm/min</td>
</tr>
<tr>
<td>Mask selectivity</td>
<td>&gt; 100 : 1</td>
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</tr>
<tr>
<td>Profile</td>
<td>87-89</td>
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Tapered profiles for SOI Trench Isolation

<table>
<thead>
<tr>
<th>Feature with Etch depth</th>
<th>2 µm deep</th>
<th>5 µm deep</th>
<th>10 µm deep</th>
<th>15 µm deep</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si etch rate</td>
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Intentional Isotropic Etch

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<tr>
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Problems and Solutions

- Trench Area Dependent Etching of Profiles
- Bowing
- RIE lag
- Micro grass
- Bottling
- Tilting

Some Real Pictures