Chapter 9, Etch

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Objectives

Upon finishing this course, you should able to:

• Familiar with etch terminology
• Compare wet and dry etch processes
• List four materials need to be etched during IC processing and list the main dry etch etchants
• Describe etch process in IC fabrication
• Become aware of hazards in etch processes
Outline

• Introduction
• Terminology
• Wet and dry etch
• Plasma basics
• Plasma etch processes
Definition of Etch

• Process that removes material from surface
• Chemical, physical or combination of the two
• Selective or blanket etch
• Selective etch transfers IC design image on the photoresist to the surface layer on wafer
• Other applications: Mask making, Printed electronic board, Artwork, etc.
Gate Mask Alignment

Gate Mask

Photoresist

Polysilicon

STI

USG

P-Well
Gate Mask Exposure

Gate Mask

Photoresist

Polysilicon

STI

USG

P-Well
Development/Hard Bake/Inspection

PR

Polysilicon

STI

USG

P-Well
Etch Polysilicon
Etch Polysilicon, Continue

Gate Oxide

Polysilicon

STI

USG

P-Well
Strip Photoresist

Gate Oxide

Polysilicon

STI

USG

P-Well
Ion Implantation

Gate Oxide  Dopant Ions, As$^+$  Polysilicon

STI  n$^+$  USG

P-Well  Source/Drain
Rapid Thermal Annealing

Gate Oxide

Polysilicon Gate

STI

n$^+$

n$^+$

USG

P-Well

Source/Drain
Wafer Process Flow

Wafers → IC Fab

Materials

Metallization → CMP

Thermal Processes

Implant PR strip

Etch PR strip

Dielectric deposition

CMP

Photo-lithography

Design

Masks

Packaging → Final Test

Test
Applications of Etch

- IC Fabrication
- Mask making
- Printed electronic board
- Art work
- Nameplate
- Glassware
Wet Etch Profiles

- Can’t be used for feature size is smaller than 3 μm
- Replaced by plasma etch for all patterned etch
CMOS Cross-Section

P-Well

n^+, LDD

P-Epi

P-Wafer

n^-, LDD

ILD-2, USG

ILD-1, BPSG

W-Plug

N-Well

USG

n^+

M2

Nitride Oxide

Al•Cu

Passivation 1

Passivation 2
Etch Terminology

- Etch rate
- Selectivity
- Etch uniformity
- Etch profile
- Wet etch
- Dry etch
- RIE
- Endpoint
Etch Rate

Etch rate measures of the how fast the material is removed from wafer surface.

\[ \Delta d = d_0 - d_1 \, (\text{Å}) \] is thickness change and \( t \) is etch time (min)
Etch Rate

Etch rate \( = \frac{\text{thickness change after etch}}{\text{etch time}} \)

PE-TEOS PSG film, 1 minute in 6:1 BOE at 22 °C,

Before etch, \( t = 1.7 \, \mu m \), After wet etch, \( t = 1.1 \, \mu m \)

\[
\text{ER} = \frac{17000 - 11000}{1} = 6000 \, \text{Å/min}
\]
Etch Uniformity

- Etch uniformity is a measure of the process repeatability within the wafer (WIW) and wafer to wafer (WTW)
- Thickness measurements are made before and after etch at different points
- More measure points, higher the accuracy
- Standard deviation definition are normally used
- Different definitions give different results
Standard Deviation Non-uniformity

N points measurements

\[
\sigma = \sqrt{\frac{(x_1 - \bar{x})^2 + (x_2 - \bar{x})^2 + (x_3 - \bar{x})^2 + \cdots + (x_N - \bar{x})^2}{N - 1}}
\]

\[
\bar{x} = \frac{x_1 + x_2 + x_3 + \cdots + x_N}{N}
\]
Max-Min Uniformity

Etch non-uniformity (NU) can be calculated by using following equation (called Max-Min uniformity, good for classroom exercise):

\[ NU(\%) = \frac{(E_{\text{max}} - E_{\text{min}})}{2E_{\text{ave}}} \]

\( E_{\text{max}} \) = Maximum etch rate measured
\( E_{\text{min}} \) = Minimum etch rate measured
\( E_{\text{ave}} \) = Average etch rate
Selectivity

- Selectivity is the ratio of etch rates of different materials.
- Very important in patterned etch
- Selectivity to underneath layer and to photoresist

\[ S = \frac{E_1}{E_2} \]
Selectivity

• Selectivity of BPSG to Poly-Si: \( S = \frac{E_1}{E_2} \)
Selectivity

\[
\text{Selectivity} = \frac{\text{Etch rate 1}}{\text{Etch rate 2}}
\]

Etch rate for PE-TEOS PSG film is 6000 Å/min, etch rate for silicon is 30 Å/min, PSG to silicon

\[
\text{Selectivity} = \frac{6000}{30} = 200:1
\]
Etch Profiles

Anisotropic

Isotropic

Anisotropic, tapered

Anisotropic, Undercut
Etch Profiles

- Anisotropic, Foot
- Undercut, reversed foot
- Undercut, reversed tapered
- Undercut, I-beam
Loading Effects: Macro Loading

• ER of a wafer with a larger open area is different from the wafer with a smaller open area
• Mainly affects the batch etch process,
• Has a minimal effect on the single wafer process
Loading Effects: Micro Loading

- Smaller hole has a lower etch rate than the larger holes
- Etchants are more difficult to pass through the smaller hole
- Etch byproducts are harder to diffuse out
- Lower pressure can minimize the effect.
- Longer MFP, easier for etchants reaching the film and for etch byproducts to get out
Micro Loading
Profile Micro Loading

Ion scattering removes the sidewall PR

Caused by PR sidewall deposition
Over Etch

- Film thickness and etch rate is not uniform
- Over etch: removes the leftover film
- Selectivity of etched film and substrate
- RIE uses optical endpoint to switch from main etch to over etch
Start Etch Process

Start main etch
Main Etch Endpoint

Before over etch

Substrate

Endpoint signal out

Δd

PR

Film
After Overetch

After over etch
Residues

• Unwanted leftovers
• Causes
  – insufficient over etch
  – non-volatile etch byproducts
Insufficient Over Etch

Before etch

Insufficient over etch

Film

Substrate

Film 1

Film 2 line A

Film 2 line B

Residue from film 2

Sidewall residue

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Non-volatile Residue on Surface
Residues

- Adequate over etch
- Removal of non-volatile residues
  - Sufficient ion bombardment to dislodge
  - Right amount of chemical etch to scoop
- Oxygen plasma ashing: Organic residues
- Wet chemical clean: inorganic residues
Wet Etch
Wet Etch

- Chemical solution to dissolve the materials on the wafer surface
- The byproducts are gases, liquids or materials that are soluble in the etchant solution.
- Three basic steps, etch, rinse and dry
Basic Wet Etch Process Steps

Etchant Sink

Spin Dryer

D.I. Wafer Rinse
Wet Etch

- Pure chemical process, isotropic profile
- Was widely used in IC industry when feature size was larger than 3 micron
- Still used in advanced IC fabs
  - Wafer clean
  - Blanket film strip
  - Test wafer film strip and clean
Wet Etch Profiles

- Can’t be used for feature size is smaller than 3 µm
- Replaced by plasma etch for all patterned etch
Applications of Wet Etch

• Wet etch can not be used for patterned etch when CD < 3 μm
• High selectivity
• It is widely used for strip etch process, such as nitride strip and titanium strip, etc.
• Also widely used for CVD film quality control (buffered oxide etch or BOE)
• Test wafers strip, clean, and reuse
Wet Etching Silicon Dioxide

• Hydrofluoric Acid (HF) Solution
• Normally diluted in buffer solution or DI water to reduce etch rate.

\[ \text{SiO}_2 + 6\text{HF} \rightarrow \text{H}_2\text{SiF}_6 + 2\text{H}_2\text{O} \]

• Widely used for CVD film quality control
• BOE: Buffered oxide etch
• WERR: wet etch rate ratio
Wide Glass Contact

Photoresist

Wet etch

Dry etch

Oxide

Metal
Wet Etching Silicon or Poly

- Silicon etch normally use mixture of nitric acid (HNO$_3$) and hydrofluoric acid (HF)
- HNO$_3$ oxidizes the silicon and HF removes the oxide at the same time.
- DI water or acetic acid can be used to dilute the etchant, and reduces the etch rate.

$$\text{Si} + 2\text{HNO}_3 + 6\text{HF} \rightarrow \text{H}_2\text{SiF}_6 + 2\text{HNO}_2 + 2\text{H}_2\text{O}$$
Isolation Formation

Nitride
Pad oxide
Silicon

Pad oxidation, LPCVD nitride
Etch nitride & pad oxide
Wet etch silicon
Grown SiO$_2$
Strip nitride, pad oxide
Wet Etching Silicon Nitride

- Hot (150 to 200 °C) phosphoric acid $H_3PO_4$ Solution
- High selectivity to silicon oxide
- Used for LOCOS and STI nitride strip

$$Si_3N_4 + 4 H_3PO_4 \rightarrow Si_3(PO_4)_4 + 4NH_3$$
Wet Etching Aluminum

• Heated (42 to 45°C) solution
• One example: 80% phosphoric acid, 5% acetic acid, 5% nitric acid, and 10 % water
• Nitric acid oxidizes aluminum and phosphoric acid removes aluminum oxide at the same time.
• Acetic acid slows down the oxidation of the nitric acid.
Wet Etching Titanium

• 1:1 mixture of hydrogen peroxide (H₂O₂) and sulfuric acid (H₂SO₄)
• H₂O₂ oxidizes titanium to form TiO₂
• H₂SO₄ reacts with TiO₂ and removes it simultaneously
• H₂O₂ oxidizes silicon and silicide to form SiO₂
• H₂SO₄ doesn’t react with SiO₂
Self-aligned Titanium Silicide Formation

Titanium deposition
Silicide annealing
Titanium wet striping
Factors that Affect Wet Etch Rate

- Temperature
- Chemical concentration
- Composition of film to be etched
Wet Chemical Hazards

• HF
• H$_3$PO$_3$
• HNO$_4$

• Corrosive
• Oxidizer
• Special hazard
Wet Chemical Hazards

- HF
- Don’t feel when contact
- Attack bone and neutralize by calcium
- Acute pain

- Never assume. Treat all unknown clear liquid as HF in IC fab.
Advantages of Wet Etch

- High selectivity
- Relatively inexpensive equipment
- Batch system, high throughput
Disadvantages of Wet Etch

• Isotropic Profile
• Can’t pattern sub-3µm feature

• High chemical usage
• Chemical hazards
  – Direct exposure to liquids
  – Direct and indirect exposure to fumes
  – Potential for explosion
Plasma Etch
Introduction

• Gas in, gas out
• Plasma generates free radicals and ion bombardment
• RIE (Reactive Ion Etch)
  – combined chemical and physical etch
• Most patterned etches are RIEs
## Comparison of Wet and Dry Etch

<table>
<thead>
<tr>
<th></th>
<th>Wet Etch</th>
<th>Dry Etch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Etch Bias</td>
<td>Unacceptable for &lt; 3µm</td>
<td>Minimum</td>
</tr>
<tr>
<td>Etch Profile</td>
<td>Isotropic</td>
<td>Anisotropic to isotropic, controllable</td>
</tr>
<tr>
<td>Etch rate</td>
<td>High</td>
<td>Acceptable, controllable</td>
</tr>
<tr>
<td>Selectivity</td>
<td>High</td>
<td>Acceptable, controllable</td>
</tr>
<tr>
<td>Equipment cost</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Throughput</td>
<td>High (batch)</td>
<td>Acceptable, controllable</td>
</tr>
<tr>
<td>Chemical usage</td>
<td>High</td>
<td>Low</td>
</tr>
</tbody>
</table>
Plasma Basics

• A plasma is an ionized gas with equal numbers of positive and negative charges.
• Three important collisions:
  – Ionization generates and sustains the plasma
  – Excitation-relaxation causes plasma glow
  – Disassociation creates reactive free radicals
Components of Plasma

• A plasma consists of neutral atoms or molecules, negative charges (electrons) and positive charges (ions)

• Quasi-neutral: \( n_i \approx n_e \)

• Ionization rate: \( \eta \approx n_e / (n_e + n_n) \)
Ionization Rate

- Ionization rate is mainly determined by electron energy in plasma
- In most plasma processing chambers, the ionization rate is less than 0.001%.
- The ionization rate of high density plasma (HDP) source is much higher, about 1%.
- Ionization rate in the core of sun is ~100%.
Mean Free Path (MFP)

• The average distance a particle can travel before colliding with another particle.

\[ \lambda = \frac{1}{n\sigma} \]

• \( n \) is the density of the particle
• \( \sigma \) is the collision cross-section of the particle
Mean Free Path (MFP)

• Effect of pressure:

\[ \lambda \propto \frac{1}{p} \]

• Higher pressure, shorter MFP

• Lower pressure, longer MFP
Vacuum and Plasma

- Pressure too high, MFP will be too short
- Ionization usually require at least 15 eV
- Electrons can’t get enough energy to ionize if MFP is too short
- Need vacuum and RF to start and maintain stabilize plasma
Ion Bombardment

- Anything close to plasma gets ion bombardment
- Very important for sputtering, RIE and PECVD
- Mainly determined by RF power
- Pressure also affects ion bombardment
Ion Bombardment

- Electrons are moving much faster than ions
- Electrons reach electrodes and chamber wall first
- Electrodes are charged negatively, repel electrons and attract ions
- Charge difference near the surface forms sheath potential
- Sheath potential accelerates ions towards the electrode and causes ion bombardment
Ion Bombardment

• Ion energy
• Ion density
• Both controlled by RF power
Applications of Ion Bombardment

• Help to achieve anisotropic etch profile
  – Damaging mechanism
  – Blocking mechanism

• Argon sputtering
  – Dielectric etch for gap fill
  – Metal deposition

• Help control film stress in PECVD processes
  – Heavier bombardment, more compressive film
Ion Bombardment Control

• Increasing RF power, DC bias increases, ion density also increases.
• Both ion density and ion bombardment energy are controlled by RF power.
• RF power is the most important knob controlling ion bombardment
Ion Bombardment Control

- RF power is the main knob to control etch rate
  - Increasing RF power, increases etch rate
  - usually reduces selectivity

- RF power also used to control film stress for PECVD processes
  - Increasing RF power increase compressive stress
Self-Bias

• Different size electrodes
• No net charge build up in plasma
• Charge fluxes on both electrodes are the same
• Smaller electrode has higher charge density
• Larger DC bias between plasma and smaller electrode
## Etch Processes

<table>
<thead>
<tr>
<th>Chemical</th>
<th>RIE</th>
<th>Physical</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Blocking Mechanism</strong></td>
<td><strong>Damaging Mechanism</strong></td>
<td></td>
</tr>
<tr>
<td>Silicon Etch</td>
<td>Oxide Etch</td>
<td></td>
</tr>
<tr>
<td>Poly Etch</td>
<td>Nitride Etch</td>
<td></td>
</tr>
<tr>
<td>Metal Etch</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Chemical Etch

• Purely chemical reaction
• By products are gases or soluble in etchants
• High selectivity
• Isotropic etch profile
• Examples:
  – Wet etch
  – Dry strip
Physical Etch

- Bombardment with inert ions such as $\text{Ar}^+$
- Physically dislodging material from surface
- Plasma process
- Anisotropic profile
- Low selectivity
- Example:
  - Argon sputtering etch
Reactive Ion Etch (RIE)

- Combination of chemical and physical etch
- Plasma process, ion bombardment plus free radicals
- Misleading name, should be called ion assistant etch (IAE)
- High and controllable etch rate
- Anisotropic and controllable etch profile
- Good and controllable selectivity
- All patterned etches are RIE processes in 8” fabs
RIE Experiment

Experiment arrangement

Experiment results
# Three Etch Processes

<table>
<thead>
<tr>
<th></th>
<th>Chemical Etch</th>
<th>RIE</th>
<th>Physical Etch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Examples</td>
<td>Wet etch, strip, RP etch</td>
<td>Plasma patterned etches</td>
<td>Argon sputtering</td>
</tr>
<tr>
<td>Etch rate</td>
<td>High to low</td>
<td>High, controllable</td>
<td>Low</td>
</tr>
<tr>
<td>Selectivity</td>
<td>Very good</td>
<td>Reasonable, controllable</td>
<td>Very poor</td>
</tr>
<tr>
<td>Etch profile</td>
<td>Isotropic</td>
<td>Anisotropic, controllable</td>
<td>Anisotropic</td>
</tr>
<tr>
<td>Endpoint</td>
<td>By time or visual</td>
<td>Optical</td>
<td>By time</td>
</tr>
</tbody>
</table>

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Etch Process Sequence

1. Generation of Etchant Species
2. Diffusion to Surface
3. Adsorption
4. Reaction
5. Desorption
6. Diffusion into convection flow

Plasma

Film

Gas Flow

Byproducts

Ion Bombardment

Boundary layer

Sheath layer
Etch Profile Control

<table>
<thead>
<tr>
<th>Damaging</th>
<th>Blocking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxide</td>
<td>Epi-silicon</td>
</tr>
<tr>
<td>Nitride</td>
<td>Polysilicon</td>
</tr>
<tr>
<td></td>
<td>Metal</td>
</tr>
</tbody>
</table>

Anisotropic profile control can be achieved by using ion bombardment from plasma
Damaging Mechanism

- Heavy ion bombardment damages chemical bonds
- Exposed surface atoms are easier to react with etchant free radicals
- Ion bombardment is mainly in vertical direction
- Etch rate on vertical direction is much higher than on horizontal direction → anisotropic etch
Damage Mechanism

- Exposed atom
- Etched Atom or molecule
- Etchant free radical
- Etch Byproduct
- Broken bonds
- PR
- Ions
Blocking Mechanism

• Chemicals deposit on the surface
• Sputtered photoresist and/or byproducts of etch chemical reaction
• Ion bombardment is mainly in vertical direction
• It prevents deposition to buildup on bottom
• Deposition on sidewall blocks etch process
• Etch process is mainly in vertical direction
Ions

Blocking Mechanism

Knocked away bottom deposition

Etched Atom or molecule
Etchant free radical
Etch Byproduct

Sidewall deposition

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## Etch Mechanisms and Their Applications

<table>
<thead>
<tr>
<th>Pure Chemical Etch</th>
<th>Reactive Ion Etch (RIE)</th>
<th>Pure Physical Etch</th>
</tr>
</thead>
<tbody>
<tr>
<td>No ion bombardment</td>
<td>Light ion bombardment</td>
<td>Heavy ion bombardment</td>
</tr>
<tr>
<td>PR strip</td>
<td>Single crystal silicon etch</td>
<td></td>
</tr>
<tr>
<td>Ti strip</td>
<td>Polysilicon etch</td>
<td>Oxide etch</td>
</tr>
<tr>
<td>Nitride strip</td>
<td>Metal etch</td>
<td>Nitride etch</td>
</tr>
</tbody>
</table>
Benefits of Using Plasma For Etch Process

- High etch rate
- Anisotropic etch profile
- Optical endpoint
Plasma Etch Chambers

• Batch system
• Single wafer system
• High density plasma system
  – IPC
  – ECR
  – Helicon
Batch Systems

- High throughput
- Older systems
- Smaller diameter, <150 mm or 6 inch
- Downstream etcher and barrel etch system
  - Both are pure chemical etch, no ion bombardment
Etch Chamber

• Lower pressure, longer MFP, less collisions
• High ion energy, less ion scattering and better anisotropy etch profile
• Lower pressure also helps to remove the etch byproducts
• Etch chambers usually operate at lower pressure
Down Stream Plasma Etcher

Process gases → Plasma → Remote Plasma Chamber → Free Radicals → Etch Chamber → Wafers

Microwave or RF

Byproducts to Vacuum Pump
Barrel Etch System
Batch RIE System

- Chamber Lid
- Wafers
- Plasma
- To Vacuum Pump
Schematic of an RIE System

Process gases

Process chamber

Wafer

By-products to the pump

Plasma

Magnet coils

Helium For backside cooling

RF Power

Chuck
Purpose of Magnets

• Long MFP, insufficient ionization collisions
• In a magnetic field, electron is forced to spin with very small gyro-radius
• Electrons have to travel longer distance
• More chance to collide
• Increasing plasma density at low pressure
Effect of Magnetic Field on DC Bias

• Magnetic field increasing electron density in sheath layer
• Less charge difference in sheath region
• Lower DC Bias
• Effects on ion bombardment
  – increasing ion density
  – reducing ion energy
Effect of Magnetic Field on DC Bias

Plasma

$B \quad E \quad e^-$

Sheath

Wafer
Wafer Cooling

- Ion bombardment generate large amount heat
- High temperature can cause PR reticulation
- Need cool wafer to control temperature
- Helium backside cooling is commonly used
- Helium transfer heat from wafer to water cooled chuck
Clamp Ring

Clamp Ring

Seal
O-ring

Helium

Water-cooled pedestal, cathode, or chuck

Wafer
Electrostatic Chuck (E-chuck)

- Helium needs to be pressurized
- Wafer has high pressure at backside because low chamber pressure
- Need mechanisms to hold wafer
- Either mechanical clamp or E-chuck
- Clamp ring causes particles and shadowing effect
- E-chuck is rapidly replacing clamp ring
Electrostatic Chuck

Plasma

Wafer

Bias Voltage

Helium

Chuck

Thermal Conducting, Electrical Insulating Layer
# Facts of Helium

<table>
<thead>
<tr>
<th>Name</th>
<th>Helium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>Helium</td>
</tr>
<tr>
<td>Symbol</td>
<td>He</td>
</tr>
<tr>
<td>Atomic number</td>
<td>2</td>
</tr>
<tr>
<td>Atomic weight</td>
<td>4.002602</td>
</tr>
<tr>
<td>Discoverer</td>
<td>Sir William Ramsay and independently by N. A. Langley and P. T. Cleve</td>
</tr>
<tr>
<td>Discovered at</td>
<td>London, England and Uppsala, Sweden</td>
</tr>
<tr>
<td>Discovery date</td>
<td>1895</td>
</tr>
<tr>
<td>Origin of name</td>
<td>From the Greek word &quot;helios&quot; meaning &quot;sun&quot;. Its line radiation (a yellow line at 587.49 nm) was first detected from the solar spectrum during in solar eclipse of 1868 in India by French astronomer,</td>
</tr>
<tr>
<td>Molar volume</td>
<td>21.0cm$^3$</td>
</tr>
<tr>
<td>Velocity of sound</td>
<td>970 m/sec</td>
</tr>
<tr>
<td>Refractive index</td>
<td>1.000035</td>
</tr>
<tr>
<td>Melting point</td>
<td>0.95 K or -272.05 C</td>
</tr>
<tr>
<td>Boiling point</td>
<td>4.22 K or -268.78 C</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>0.1513 W m$^{-1}$ K$^{-1}$</td>
</tr>
<tr>
<td>Applications</td>
<td>Cooling gas and carrier gas in CVD and etch processes</td>
</tr>
</tbody>
</table>

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High Density Plasma (HDP) Sources

- Low pressure is desired for etch process
- Electrons are easily lost due to long MFP by collide with electrodes or chamber wall
- Hard to generate plasma
- Parallel plate system or capacitive coupled system can not generate high density plasma
- Different plasma systems are needed to generate HDP at low pressure
HDP Systems

- Inductively coupled plasma (ICP)
- Electron cyclotron resonance (ECR)
- Helicon
ICP

- Inductively couple RF power to plasma
- Like a transformer, also called TCP
- Changing magnetic field cause electric field
- Electrons are accelerated in angular direction
- Could achieve high plasma density at low pressure
ICP Chamber

- Upper part of chamber: ceramic or quartz
- Source RF inductively couple with plasma
- Source RF generates plasma and controls ion density
- Bias RF controls ion bombardment energy
- Ion energy and density independently controlled
Schematic of ICP Chamber

- Process gases
- Process chamber
- Wafer
- Byproducts to the pump
- Helium backside cooling
- Plasma
- Source RF
- RF coils
- E-Chuck
- Bias RF
ECR

• In magnetic field, electron gyro-frequency
  \[ \Omega_e \text{ (MHz)} = 2.80 \ B \text{ (Gauss)} \]
• If incident microwave frequency equals to \( \Omega_e \)
  \[ \omega_{MW} = \Omega_e \]
• Resonance
• Electrons get energy from microwave
ECR

- Resonance condition won’t change with fixed $\omega_{MW}$ and $B$
- Electrons gyro-radius, $\rho = v_t/\Omega_e$ is very small
- Electron can be accelerated to high energy for ionization collision
- Generate high density plasma at low pressure
Illustration of ECR
Schematic of ECR Chamber

- Magnetic Coils
- Magnetic field line
- E-chuck
- Bias RF
- Helium
- Microwave
- ECR Plasma
- Wafer
Endpoint

• Each atom has its own emission wavelength
• Color of plasma changes when etch different materials
• Optical sensors can be used to detect the change and indicate the endpoint for plasma etch processes
## Etch Endpoint Wavelengths

<table>
<thead>
<tr>
<th>Film</th>
<th>Etchant</th>
<th>Wavelength (Å)</th>
<th>Emitter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>Cl₂, BCl₃</td>
<td>2614</td>
<td>AlCl</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3962</td>
<td>Al</td>
</tr>
<tr>
<td>Poly Si</td>
<td>Cl₂</td>
<td>2882</td>
<td>Si</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6156</td>
<td>O</td>
</tr>
<tr>
<td>Si₃N₄</td>
<td>CF₄/O₂</td>
<td>3370</td>
<td>N₂</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3862</td>
<td>CN</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7037</td>
<td>F</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6740</td>
<td>N</td>
</tr>
<tr>
<td>SiO₂</td>
<td>CF₄ and CHF₃</td>
<td>7037</td>
<td>F</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4835</td>
<td>CO</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6156</td>
<td>O</td>
</tr>
<tr>
<td>PSG, BPSG</td>
<td>CF₄ and CHF₃</td>
<td>2535</td>
<td>P</td>
</tr>
<tr>
<td>W</td>
<td>SF₆</td>
<td>7037</td>
<td>F</td>
</tr>
</tbody>
</table>
Plasma Etch Processes
Advantage of the Plasma Etch

• High, controllable etch rate
• Good selectivity
• Anisotropic etch profile

• Disadvantage: expensive, complicated system
  – Vacuum, RF, robot, E-chuck and etc.
Etch Mechanisms and Requirements

- Oxide etch using damaging mechanism
- More physical than chemical
- Higher RF power and lower pressure
- Silicon and metal etches using blocking mechanism
- Chemical than physical
- Usually require less RF power
PLASMA ETCH

• Etch dielectric
• Etch single crystal silicon
• Etch polysilicon
• Etch metal
• Summary
Dielectric Etch

• **Etch oxide**
  – Doped and undoped silicate glass
  – Contact (PSG or BPSG)
  – Via (USG, FSG or low-\(\kappa\) dielectric)

• **Etch nitride**
  – STI
  – Bonding pad
Dielectric Etch

- Fluorine chemistry

\[ 4F + \text{SiO}_2 \rightarrow \text{SiF}_4 + 2\text{O} \]

- \( \text{CF}_4 \) is commonly used as fluorine source
- \( \text{NF}_3 \) and \( \text{SF}_6 \) have also been used
### Some Facts About Fluorine

<table>
<thead>
<tr>
<th>Name</th>
<th>Fluorine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
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</tr>
<tr>
<td>Symbol</td>
<td>F</td>
</tr>
<tr>
<td>Atomic number</td>
<td>9</td>
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<tr>
<td>Atomic weight</td>
<td>18.9984032</td>
</tr>
<tr>
<td>Discoverer</td>
<td>Henri Moissan</td>
</tr>
<tr>
<td>Discovered at</td>
<td>France</td>
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<tr>
<td>Discovery date</td>
<td>1886</td>
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<td>Origin of name</td>
<td>From the Latin word &quot;fluere&quot; meaning &quot;to flow&quot;</td>
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<td>Molar volume</td>
<td>11.20 cm³</td>
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<td>Velocity of sound</td>
<td>No data</td>
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<tr>
<td>Refractive index</td>
<td>1.000195</td>
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<tr>
<td>Melting point</td>
<td>53.53 K or -219.47 C</td>
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<tr>
<td>Boiling point</td>
<td>85.03 K or -187.97 C</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>0.0277 W m⁻¹ K⁻¹</td>
</tr>
<tr>
<td>Applications</td>
<td>Free fluorine as the main etchant for silicon oxide and silicon nitride etching processes</td>
</tr>
</tbody>
</table>

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Contact Etch

• Holes connect silicon to metal lines
• Doped silicate glass, PSG for BPSG
• Fluorine form CF$_4$ as the main etchant
• CHF$_3$ as polymer precursor to improve selectivity to silicon and silicide
• Ar to improve damaging effect
• Some people also use O$_2$ or H$_2$
• High selectivity to Si or silicide is required
Contact Etch

- Etch PSG or BPSG
- Open contact hole for silicon to metal interconnections
- Need high selectivity over silicide and photoresist
- Fluorine chemistry

\[ F + \text{SiO}_2 \rightarrow \text{SiF}_4 + O \]

\[ \text{gas} \quad \text{solid} \quad \text{gas} \quad \text{gas} \]
CMOS Cross-section

Titanium/Titanium Nitride  TiN ARC  Titanium

STI  n⁺  n⁺  USG  p⁺  p⁺  N-Well

P-Well

P-Epi

P-Wafer
Challenge for Contact Etch

- Contact holes to polyside gate and local interconnection are about half of the depth of source/drain contact holes
- Require high (B)PSG to silicide selectivity
Contact Etch

\[ \Delta t \]

\[ t \]

Photoresist

BPSG

STI

\( n^+ \)

\( \text{TiSi}_2 \)
Contact Etch

- F/C ratio
  - F/C > 3, etch dominant
  - F/C < 2, polymerization

- When etching oxide, oxygen byproduct can react with C to free more fluorine

- When etching silicon or silicide, no oxygen releasing, fluorine is consumed, F/C ratio drop below 2 and start polymer deposition

- Polymer blocks further etch process

- High BPSG-to-TiSi$_2$ selectivity
Dielectric Etch

\[ \text{plasma} \quad \text{CF}_4 \quad \rightarrow \quad \text{CF}_3 + \text{F} \]

\[ \text{plasma} \quad 4\text{F} + \text{SiO}_2 \quad \rightarrow \quad \text{SiF}_4 + 2\text{O} \]

\[ \text{plasma} \quad 12\text{F} + \text{TiSi}_2 \quad \rightarrow \quad \text{TiF}_4 + 2\text{SiF}_4 \]
F/C Ratio, DC Bias and Polymerization

![Graph showing F/C Ratio, DC Bias, and Polymerization]

- **Bias (Volts)**
  - -200
  - -100
  - 0

- **F/C Ratio**
  - 1
  - 2
  - 3
  - 4

- **Chemicals**
  - $C_2F_4$
  - $C_2F_6$
  - $CF_4$

- **Areas**
  - Polymerization
  - Etching
Via Etch

- Etch USG
- Open via hole for metal to metal interconnections
- Need high selectivity over metal and photoresist
- Fluorine chemistry
Etch Via

• PR mask
• Fluorine as the main etchant
• CF$_4$, CHF$_3$ and Ar are used for the etch process. O$_2$ or H$_2$ also can be used
• High selectivity over metal
• Avoiding metal sputtering
• Dual damascene etch
# Summary of Dielectric Etch

<table>
<thead>
<tr>
<th>Name of etch</th>
<th>Hard mask</th>
<th>Contact</th>
<th>Via</th>
<th>Bonding pad</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials</td>
<td>Si₃N₄ or SiO₂</td>
<td>PSG or BPSG</td>
<td>USG or FSG</td>
<td>Nitride and oxide</td>
</tr>
<tr>
<td>Etchants</td>
<td>CF₄, CHF₃</td>
<td>CF₄, CHF₃, ...</td>
<td>CF₄, CHF₃, ...</td>
<td>CF₄, CHF₃, ...</td>
</tr>
<tr>
<td>Underneath layer</td>
<td>Si, Cu, Au,</td>
<td>Poly or silicide</td>
<td>Metal</td>
<td>Metal</td>
</tr>
<tr>
<td>Endpoints</td>
<td>CN, N or O</td>
<td>P, O, and F</td>
<td>O, Al and F</td>
<td>O, Al and F</td>
</tr>
</tbody>
</table>

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Single Crystal Silicon Etch

- Shallow trench isolation (STI)
- Deep trench for capacitor
- Hard mask, silicon nitride and oxide
- PR may cause substrate contamination
- Bromine chemistry
- HBr as the main etchant
CMOS Cross-Section

Single Crystal Silicon Etch

TiN ARC
Titanium

STI USG

W BPSG

Al-Cu Alloy

n⁺ n⁺ USG

p⁺ p⁺

P-Well

N-Well

P-Epi

P-Wafer

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Deep Trench Capacitor

Etch hard mask

Etch silicon

Capacitor Formation

Heavily Doped Silicon

Poly-Si

SiO₂

PR

SiO₂

Si
### Some Facts About Bromine

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>Name</td>
<td>Bromine</td>
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<tr>
<td>Symbol</td>
<td>Br</td>
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<tr>
<td>Atomic number</td>
<td>35</td>
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<td>Atomic weight</td>
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<tr>
<td>Discoverer</td>
<td>Antoine-J. Balard</td>
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<td>Discovered at</td>
<td>France</td>
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<td>Discovery date</td>
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<td>Origin of name</td>
<td>From the Greek word &quot;bromos&quot; meaning &quot;stench&quot;</td>
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<td>Velocity of sound</td>
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<td>Resistivity</td>
<td>$&gt; 10^{18}$ µΩ cm</td>
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<td>Refractive index</td>
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<tr>
<td>Melting point</td>
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<tr>
<td>Boiling point</td>
<td>59 °C</td>
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<td>Thermal conductivity</td>
<td>0.12 W m⁻¹ K⁻¹</td>
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<td>Applications</td>
<td>Free bromine as the main etchant for single crystal silicon etching processes</td>
</tr>
<tr>
<td>Source</td>
<td>HBr</td>
</tr>
</tbody>
</table>
Single Crystal Silicon Etch Chemistry

plasma

$$\text{HBr} \rightarrow \text{H} + \text{Br}$$

$$\text{Br} + \text{Si} \rightarrow \text{SiBr}_4$$

• Small amount O$_2$ for sidewall passivation
• A little NF$_3$ for preventing black silicon
• Endpoint by time
Polysilicon Etch

- Gates and local interconnections
  - Most critical etch process, smallest CD
- Capacitor electrodes for DRAM
- Require high selectivity over silicon dioxide
- Cl\textsubscript{2} chemistry

\[
\text{Cl} + \text{Si} \rightarrow \text{SiCl}_4
\]

- gas \quad \text{solid} \quad \text{gas}
# Some Facts About Chlorine

<table>
<thead>
<tr>
<th>Name</th>
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<td>Atomic weight</td>
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<td>Discoverer</td>
<td>Carl William Scheele</td>
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<td>Sweden</td>
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<td>1774</td>
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<td>Origin of name</td>
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<td>Molar volume</td>
<td>17.39 cm$^3$</td>
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<tr>
<td>Velocity of sound</td>
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<tr>
<td>Resistivity</td>
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<td>Refractive index</td>
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<tr>
<td>Melting point</td>
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<tr>
<td>Boiling point</td>
<td>-33.89 °C or 239.11 K</td>
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<tr>
<td>Thermal conductivity</td>
<td>0.0089 W m$^{-1}$ K$^{-1}$</td>
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<tr>
<td>Applications</td>
<td>Used as the main etchant for poly silicon and metal etching processes. Polysilicon, epitaxy silicon deposition chamber clean.</td>
</tr>
<tr>
<td>Sources</td>
<td>Cl$_2$, HCl</td>
</tr>
</tbody>
</table>
Gate etch

Polysilicon gate

STI

USG

P-Well

N-Well

P-Epi

P-Wafer
Polysilicon Etch

• Cl$_2$ as the main etchant
• HBr for sidewall passivation, blocking mechanism
• Add O$_2$ in over etch step to improve selectivity to SiO$_2$.
• High selectivity over SiO$_2$ is required
Polysilicon Etch

- High poly-to-oxide selectivity is required

Single Crystal Silicon Substrate

- Gate Oxide
- Polysilicon
- Photoresist
- SiCl₄
Polysilicon Etch
Polysilicon Etch

Process steps:

• Breakthrough
  – Removal of native oxide, energetic Ar$^+$ bombardment

• Main etch
  – High poly etch rate, Cl and HBr chemistry
  – Endpoint on O line

• Over etch
  – Reduce power, add O$_2$ for high selectivity over SiO$_2$
Metal Etch

- Etch TiN/Al·Cu/Ti metal stack to form metal interconnection
- Usually use Cl$_2$ + BCl$_3$ chemistry
- Need etch away Cu in Al either physically or chemically
- Need strip photoresist before wafer exposure to moisture in atmosphere
CMOS Cross-section

- Titanium/Titanium Nitride
- TiN ARC
- Titanium
- STI
- USG
- BPSG
- W
- Al-Cu Alloy
- n^+
- n^+
- p^+
- p^+
- P-Well
- N-Well
- P-Epi
- P-Wafer

Metal Etch
Etch Metal

• For metal interconnection
• Metal stack: TiN/Al•Cu/Ti
• Cl₂ as the main etchant
• BCl₃, N₂ are used for sidewall passivation
• O₂ is used to improve selectivity to oxide
• Main challenges: etch profile and avoiding etch residue
• Metal grain size can affect etch process
Metal Etch Chemistries

\[ \text{Cl}_2 \rightarrow \text{Cl} + \text{Cl} \]

\[ \text{Cl} + \text{Al} \rightarrow \text{AlCl}_3 \]

\[ \text{Cl} + \text{TiN} \rightarrow \text{TiCl}_4 + \text{N} \]

\[ \text{Cl} + \text{Ti} \rightarrow \text{TiCl}_4 \]
Photoresist Dry Strip

- Remote plasma source
  - Free radicals without ion bombardment
- High pressure, microwave plasma
- Very important to strip chlorine containing PR after metal etch to avoid metal corrosion
- In-situ with etch process in a cluster tool
- Improve throughput and yield
Photoresist Dry Strip

- $O_2$, $H_2O$ chemistry

  plasma

\[
H_2O \rightarrow 2H + O
\]

\[
H + Cl \rightarrow HCl
\]

\[
O + PR \rightarrow H_2O + CO + CO_2 +
\]
Photoresist Strip Process

Microwave

Remote plasma chamber

\( H_2O, O_2 \rightarrow \text{Plasma} \)

Process chamber

Wafer with photoresist

\( O \rightarrow H \rightarrow O \rightarrow H \rightarrow O \rightarrow H \rightarrow O \)

Heated plate

\( H_2O, CO_2, HCl \ldots \)

To the pump

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Dry Chemical Etch

- Unstable gases, such as XeF$_2$ and O$_3$
- Remote plasma source free radicals
- Free from ion bombardment
- Thin film strip and wineglass contact etch
- In-situ with RIE chambers on one frame
- Nitride strip in both LOCOS and STI
- Nitride and Poly-Si strip in PBL
Blanket Dry Etch

• No photoresist. Etchback and film strip.
• Argon sputtering etch
  – Dielectric thin film applications
  – native oxide clean prior to metal deposition
• RIE etchback system
  – Can be used in-line with dielectric CVD tools
  – Sidewall spacer formation
  – PR or SOG planarization etchback
CVD $O_3$-TEOS USG

Polysilicon Gate

$\text{n}^{-}$ LDD

Gate Oxide

$\text{n}^{-}$ LDD
O$_3$-TEOS USG Etchback

Polysilicon Gate

n$^-$ LDD

Gate Oxide

n$^-$ LDD
$O_3$-TEOS USG Etchback

Polysilicon Gate

n$^-$ LDD

Gate Oxide

n$^-$ LDD
O$_3$-TEOS USG Etchback

Polysilicon Gate

n$^-$ LDD

Gate Oxide

n$^-$ LDD
$O_3$-TEOS USG Etchback

Polysilicon Gate

n\textsuperscript{-} LDD

Gate Oxide

n\textsuperscript{-} LDD
$\text{O}_3$-TEOS USG Etchback

Polysilicon Gate

n$^-$ LDD

Gate Oxide

n$^-$ LDD
O$_3$-TEOS USG Etchback

Polysilicon Gate

n$^-$ LDD

Gate Oxide

n$^-$ LDD
O$_3$-TEOS USG Etchback

Sidewall Spacer

Polysilicon Gate

Sidewall Spacer

n$^-$ LDD

Gate Oxide

n$^-$ LDD
Etch Safety

- Corrosive and toxic gases
  - \( \text{Cl}_2, \text{BCl}_3, \text{SiF}_4 \) and \( \text{HBr} \)
  - Could be fatal if inhalation at a high concentration (>1000 ppm)
- RF power can cause electric shock
- Can be lethal at high power
Etch Safety

• All moving parts, are mechanical hazards
• May cause injury if one does not stay clear
• Lock-out, tag-out
RF Power

- Increasing RF power increases ion density, ion bombardment energy, and number of free radicals
- Etch rate will increase significantly
- The most important “knob” that controls etch rate
- Check RF system first if etch rate is out of specifications
Plasma Etch Trends

![Graph showing the relationship between Etch Rate (ER), Selectivity, and RF Power.]

- Etch Rate
- Selectivity
- RF Power

ER Selectivity
Pressure

• Pressure affects plasma density and shape
• Has strong effects on etch uniformity
Etch Trends

RF ↑

Pressure ↑

B ↑
Future Trends for Etch Processes

• High density plasma (HDP) at low pressure
  – Improve profile control
  – Increasing plasma density
  – Ion bombardment flux

• Independent ion flux and ion energy control

• HDP etchers in IC processing: ICP & ECR

• Helicon plasma source: ~100% ionization, candidate for future etch chamber design
Helicon Plasma Source

- Antenna
- Source RF
- Magnetic Coils
- Plasma
- Wafer
- Magnetic field line
- Helium
- E-chuck
- Bias RF
Future Trends for Etch Processes

- 300 mm system
- Plasma uniformity control
- Plasma position control
Copper Etch?

- Cl<sub>2</sub> chemistry
- Low pressure (< 5 mTorr)
- High temperature (>250 °C)
  - Cannot use photoresist
  - Need CVD oxide hard mask
- Competition with dual damascene process
- Very unlike can be used in IC production
Direct Hard Masking Photolithography

PECVD Si-PR

Exposure, partially oxidation of Si-PR

Cl\textsubscript{2} plasma removes unexposed Si-PR

Down Stream O\textsubscript{2} fully oxidation of Si-PR
Future Trends

• Challenges ahead:
• Etch high-\(\kappa\) materials of gate dielectric and capacitor dielectric
• Etch low-\(\kappa\) materials of inter-metal dielectric
Summary

• Plasma etch is widely used for patterned etch process to transfer image on photoresist to surface materials.

• Epi, poly, oxide and metal
• Fluorine for oxide etch
• HBr for single crystal silicon etch
• Chlorine for polysilicon and metal etch
Summary

• Certain vacuum and constant RF power are need to strike and maintain a stable plasma
• RF power is main knob to control etch rate
• Pressure affects uniformity and etch profile
• High plasma density at low pressure are desired for etch deep sub-micron features.
• Dry chemical etch can be achieved with remote plasma source