EE 527 MICROFABRICATION

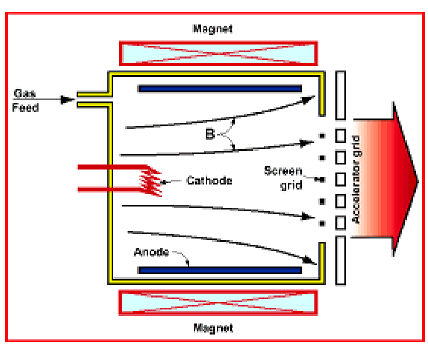
Lecture 25

Tai-Chang Chen
University of Washington

UNIVERSITY OF WASHINGTON

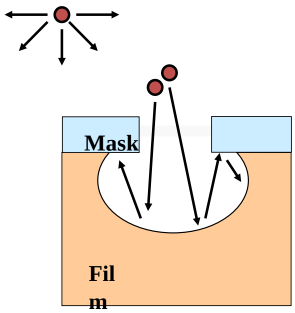
ION MILLING SYSTEM

- Kaufmann source
  - Use e-beam to strike plasma
  - A magnetic field applied to increase ion density
- Drawback
  - Low etch rate
  - High ion bombardment damage
  - redeposition



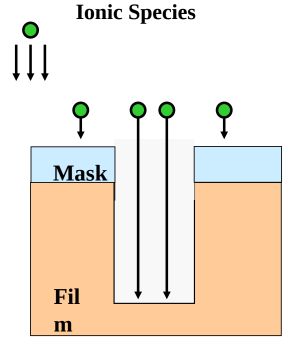
CHEMICAL VS. PHYSICAL ETCH

Reactive Species



- Wide arrival angle
- High selectivity
- Isotropic etch profile

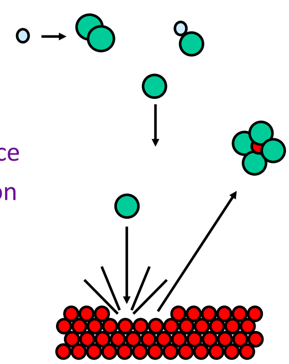
Ionic Species



- Narrow, vertical arrival
- Low selectivity
- Anisotropic etch profile

REACTIVE ION ETCHING

- Replacing the neutral gas by one or more chemical species
- Chemical etching and physical ion bombardment
  - Reactive ions damage wafer surface
  - Dangling bonds = chemical reaction sites
  - Increases etch rate
- Anisotropic
- High selectivity
- Low pressure process



RIE - ADVANTAGES AND ISSUES

- Advantages
  - Control of selectivity/anisotropy, etc. by adjusting etch process parameter
  - Minimizes shortcomings of pure sputter and chemical dry etch
- Issues
  - Unbalanced etch process parameters
  - Loading/uniformity effects
  - High ion energies can cause device damage
  - Chemicals/byproducts environmentally toxic
    - Hydrocarbon-based

SILICON – FLUORINE CHEMISTRY

- A fluorine source, such as SF_6 or CF_4 can be cracked by the plasma to produce F^- radicals.
- The F^- radicals will preferentially bind to exposed Si atoms, displacing other atoms sitting on these sites.
- Once 4 F^- radicals have saturated the available bonds of a Si atom, the SiF_4 will desorb as a volatile species.
- Bond energies:
  - Si-Si: 52 kcal/mole (energy to break a bond in single crystal Si)
  - F-F: 36.6 kcal/mole (energy to break a bond in F_2)
  - S-F: 68 kcal/mole (energy to break a bond in SF_6)
  - C-F: 116 kcal/mole (energy to break a bond in CF_4)
  - Si-F: 135 kcal/mole (energy supplied by creating a bond in SiF_4)
- F_2 and SF_6 will etch Si with no additional supplied energy.
- CF_4 will etch Si, but requires a little additional energy.

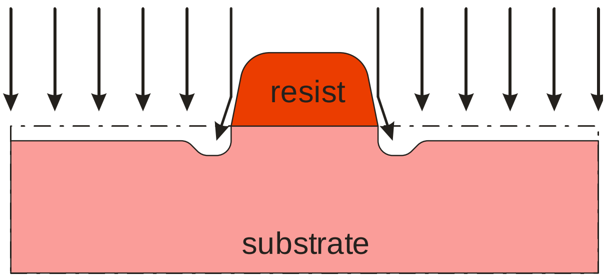
SILICON – CHLORINE CHEMISTRY

- Analogous to fluorocarbons, chlorocarbons can be cracked by the plasma, producing Cl^- radicals, which can then combine with Si to form $SiCl_4$, which is volatile and desorbs from the etched surface.
- Bond energies:
  - Si-Si: 52 kcal/mole (energy to break a bond in single crystal Si)
  - Cl-Cl: 58 kcal/mole (energy to break a bond in Cl_2)
  - C-Cl: 81 kcal/mole (energy to break a bond in CCl_4)
  - Si-Cl: 90 kcal/mole (energy supplied by creating a bond in $SiCl_4$)
- Chlorine etching always requires additional energy from the plasma, so it is always anisotropic.

GAS FEEDSTOCK RULES OF THUMB

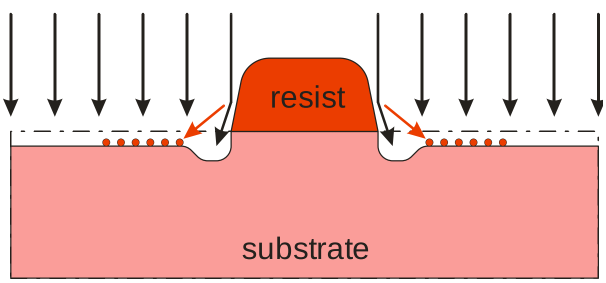
- For etching Si:
  - Fluorines are natively isotropic. Adding oxygen makes them increasingly anisotropic.
  - Chlorines are natively anisotropic.
- Oxygen will ash most organic films, such as photoresist residue, producing CO_2 and H_2O. Don't add oxygen if a fluorocarbon sidewall passivation is desired, as the O_2 will remove it.
- Hydrogen will create HF with a fluorine chemistry and produce etching of SiO_2, often preferentially to that of Si. This can be useful for sidewall passivation to achieve higher anisotropy, and for achieving greater SiO_2/Si etch selectivity.
- Argon will not affect the chemistry, but can be added when additional ion bombardment is needed. This makes most etches more anisotropic, but dilutes the reacting species.

PLASMA ETCHING EFFECTS – TRENCHING



Trenching of substrate occurs adjacent to resist edges.

PLASMA ETCHING EFFECTS – REDEPOSITION



Redeposition of sputtered resist occurs adjacent to resist edges.

SIDEWALL POLYMERIZATION – 1

- Most RIE processes exhibit some degree of sidewall passivation.
- Sidewalls receive less ion bombardment which can allow passivation reactions to dominate over etching.
- The bottom of a trench receives maximum ion bombardment which prevents the passivation layer from building up.
- Example: SF_6 / O_2: SF_6 is normally almost isotropic, but dilution with O_2 allows SiO_2 to form on sidewalls which passivates further sidewall etching. More O_2 makes the etch increasingly anisotropic.
- Example: CF_4 / H_2: Fluorocarbons can etch or polymerize depending upon the F/C ratio: $F/C > 3$ gives etching, $F/C < 2$ gives polymerization. Adding H_2 forms HF which can etch oxides, giving Si/SiO_2 selectivity. Forming HF also reduces the available F^-, so polymerization is enhanced. CHF_3 is also used for achieving this.

SIDEWALL POLYMERIZATION – 2

- Fluorocarbon RIE usually creates a $–CF_2–$ polymer on the sidewalls, similar to Teflon® PTFE.
- The chemical inertness of this polymer can be useful for subsequent process steps, but this also makes its removal difficult. Oxygen plasma ashing is usually needed for removal.
- For low to moderate trench aspect ratios (depth : width), this polymerization can produce nearly vertical RIE sidewalls.
- For deeper trenches, it becomes increasingly difficult to keep the sidewalls shielded from bombardment from glancing angle ions, and the polymer layer is eroded as fast as it is created.
- Single chemistry RIE reaches a limiting aspect ratio of around unity for near vertical sidewall profiles.
- A solution is to use a two-chemistry / two-phase approach.
  - This is the basis for DRIE.

Types of Etching	Methods	Geometry	Selectivity	Excitation Energy	Pressure
Gas/vapor Etching	Chemical	Isotropic	Very high	none	High (760-1torr)
Plasma Etching	Chemical	Isotropic	High	10's to 100's of Watts	Medium (>100 mtorr)
Reactive ion Etching	Chemical & Physical	Directional	Fair	100's of Watts	Low (10-100 mtorr)
Sputtering Etching	Physical	Directional	Low	100's to 1000's of Watts	Low (~10 mtorr)

(1 torr = 1 mmHg)

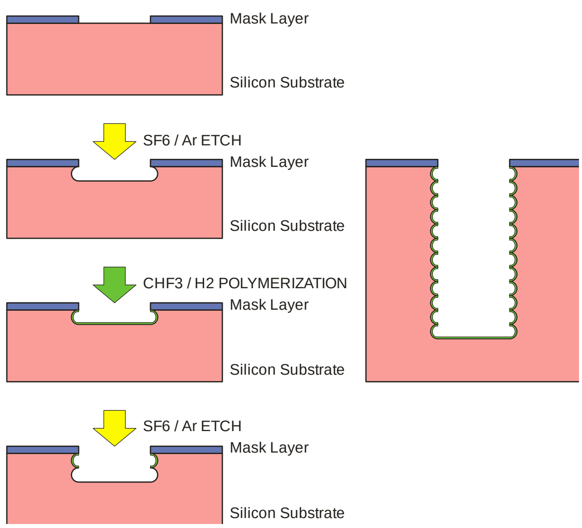
DRIE- DEEP REACTIVE ION ETCH

- This is one of the few process tools that was developed specifically for MEMS applications.
- Special type of RIE
  - "Tricks" needed to increase the aspect ratio
  - Requires high density plasma (HDP) systems
- RIE works up to 4:1 aspect ratio
  - Sidewalls can etch causing non-straight features
- DRIE methods can create up to 30:1 aspect ratio!

DEEP REACTIVE ION ETCHING (DRIE)

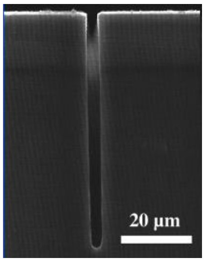
- Lärmer and Schilp (Bosch) Deutsch patent of 1994:
  - Alternate between etching and polymer deposition. (2 phases)
  - Etching phase removes the polymer on the bottom of the trench.
  - Polymerization phase protects the sidewalls from etching.
- Etching phase:
  - SF_6 / Ar used with -5 to -30 V of substrate bias to produce nearly vertical incident ions. This creates an anisotropic SF_6 etch without needing O_2.
- Polymerization phase:
  - CHF_3 or C_4H_8 / SF_6 used. The sidewall polymer is $–CF_2–$, teflon-like.
- Can obtain nearly vertical sidewalls with ~30:1 aspect ratios.
- Sidewalls have a characteristic scalloping that corresponds to each cycle of the etching / polymerization phases.

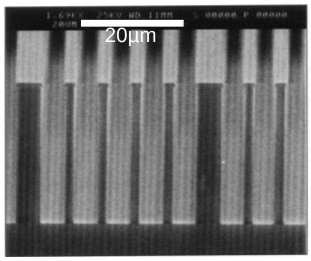
DRIE PROCESS



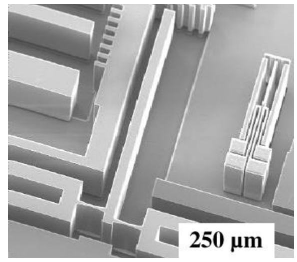
DRIE EXAMPLES

- Commercial equipment is produced by STS, Plasma-Therm, Oxford Instruments, and Trion.





STS '99



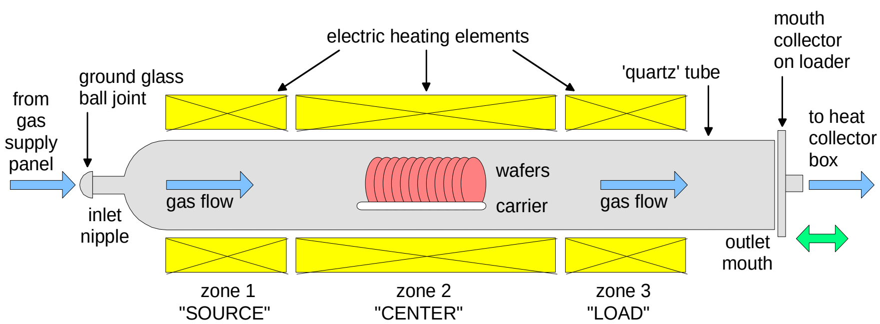
Klaassen et al. '95 (Stanford)

TUBE FURNACES

- The industry standard for achieving processing temperatures in the range of ~800 to 1200°C with tight control of temperature and gas flows.
- Horizontal style
  - Traditional, most common for laboratory R&D work.
  - Multi-tube stacks (4 ea.) were very common for production work.
- Vertical style
  - Newer technology, most common for IC production.
  - Better suited for larger wafers sizes (> 200 mm).
- Both use electrically heated furnace blocks that surround a quartz (fused silica) tube.

3-ZONE HORIZONTAL FURNACE TUBE - ATMOSPHERIC

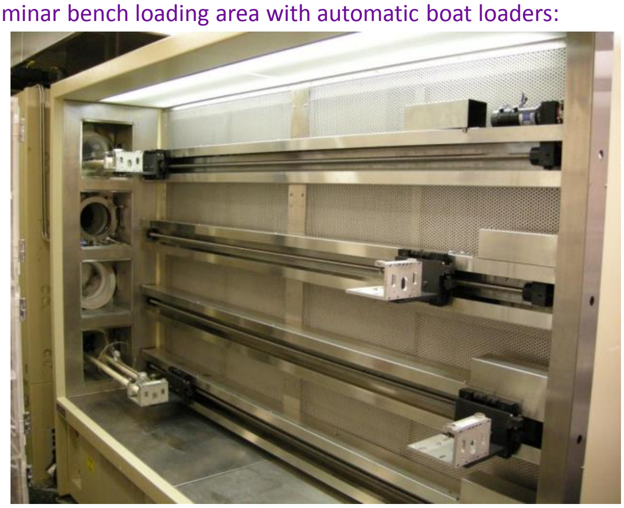
Atmospheric pressure system:



3-zone tube furnaces are most common, but 5-zone tube furnaces also exist.

4-TUBE SEMI-PRODUCTION FURNACE STACK

- Laminar bench loading area with automatic boat loaders:



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