Dry Etching

Dr. Bruce K. Gale

Fundamentals of Micromachining

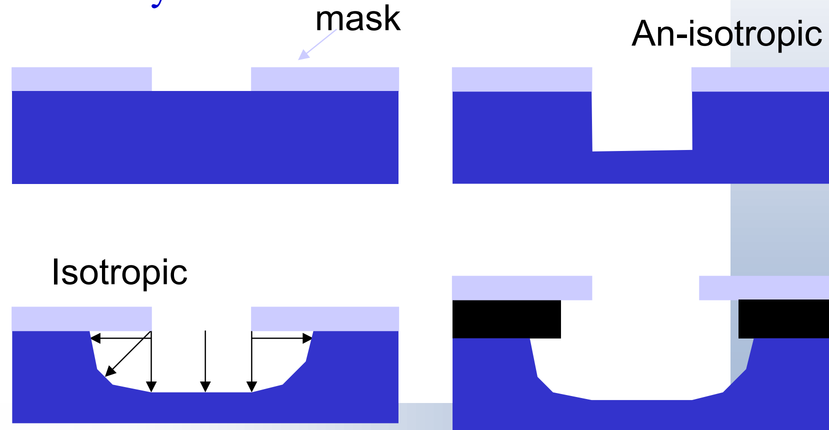
BIOEN 6421

EL EN 5221 and 6221

ME EN 5960 and 6960

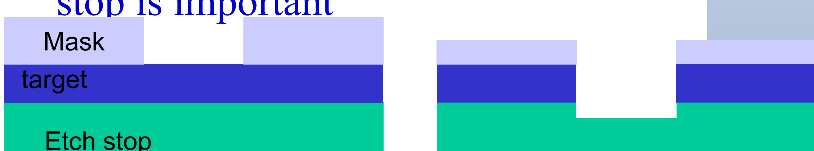
Etching Issues - Anisotropy

- Isotropic etchants etch at the same rate in every direction



Etching Issues - Selectivity

- Selectivity is the ratio of the etch rate of the target material being etched to the etch rate of other materials
- Chemical etches are generally more selective than plasma etches
- Selectivity to masking material and to etch-stop is important



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

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)

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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

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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

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Xenon Difluoride (XeF_2) Etching

- Isotropic etching of Si
- High selectivity for Al, SiO_2, Si_3N_4, PR, PSG
- $2XeF_2 + Si \rightarrow 2Xe + SiF_4$
- Typical etch rates of 1 to 3 µm/min
- Heat is generated during exothermic reaction
- XeF_2 reacts with water (or vapor) to form HF

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Interhalogen (BrF_3 & ClF_3) Etching

- Nearly isotropic profile
- Gases react with Si to form SiF_4
- Surface roughness: ~40 to 150 nm
- Masks: SiO_2, Si_3N_4, PR, Al, Cu, Au, and Ni

Plasma Based Dry Etching

- RF power is used to drive chemical reactions
- Plasma takes place of 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
- $KE = \frac{1}{2} mV^2 = \frac{3}{2} kT$
  - – m = particle mass
  - – V = particle mean velocity
  - – k = Boltzmann constant
  - – T = temperature (K)

2 eV electron has
$T \approx 15,000$ K
$V \approx 6 \times 107$ 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

Plasma Formation

- Plasma discharge is characterized by central glow or bulk region and dark or sheath regions near electrodes
- Bulk region = semi-neutral (nearly equal number of electrons and ions)
- Sheath regions = nearly all of the potential drop; accelerates "+" ions from bulk region which bombard the substrate
- Maintained at 1 Pa (75 mtorr) to 750 Pa (56 torr) with gas density of 27 x 10^{14} to 2 x 10^{17} molecules/cm^3

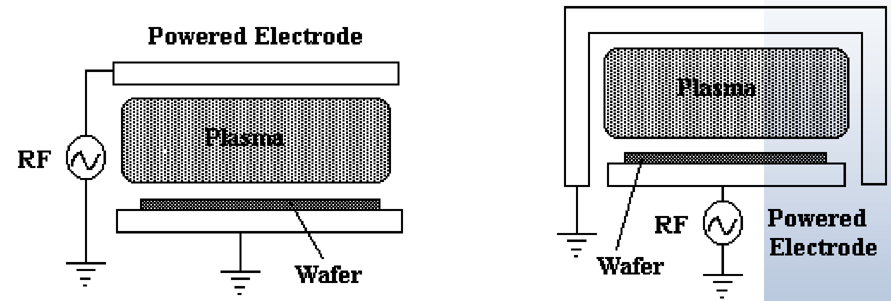
Plasma Parameters

- 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 (microloading)
  - 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 (ie, no masking)
- Argon is the most commonly used ion source
- May result in redeposition

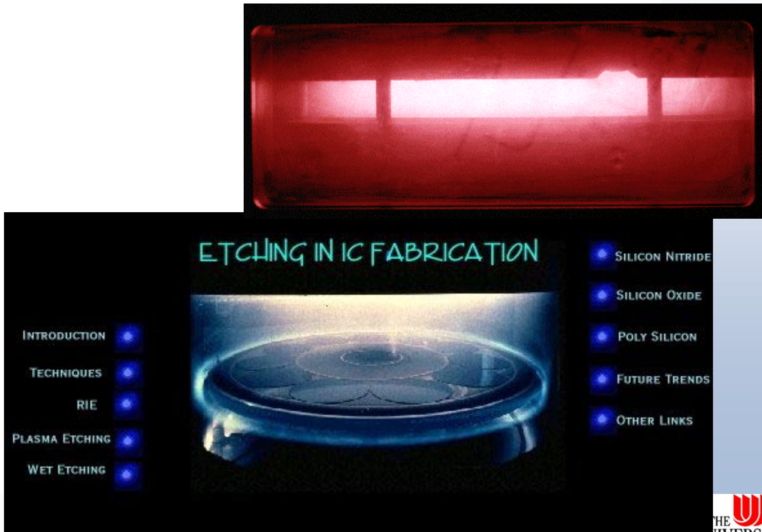
Two Basic Plasma Systems



PE: grounded wafer; symmetrical electrode.

RIE: powered wafer; grounded surface area much larger than powered electrode.

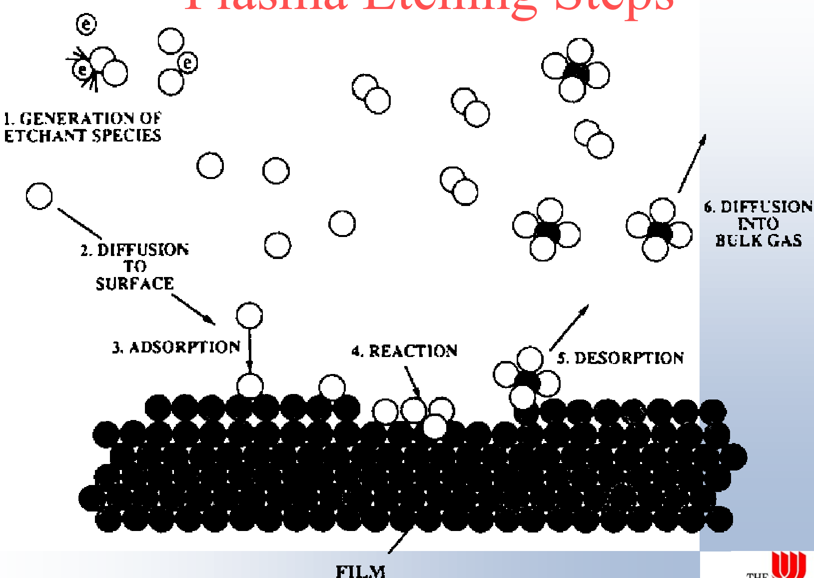
Plasma Etchers



Chemical (Plasma) Etching:

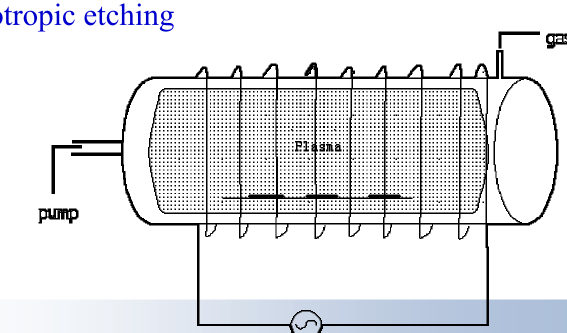
- Plasma is used to produce chemically reactive species (atoms, radicals, and ions) from inert molecular gas
- Six major steps:
  - Generation of reactive species (eg, free radicals)
  - Diffusion to surface
  - Adsorption on surface
  - Chemical reaction
  - Desorption of by-products
  - Diffusion into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

Plasma Etching Steps



Plasma Etching Systems

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



Reactive Ion Etching (RIE)

- RIE = process in which chemical etching is accompanied by ionic bombardment (ie 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

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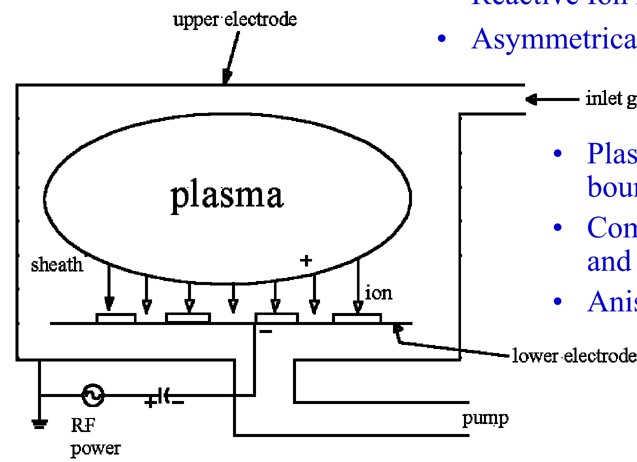
RIE System

- Reactive Ion Etching (RIE)
- Asymmetrical parallel plate system



- Plasma, sheath and boundary layer
- Combination of physical and chemical etching
- Anisotropic etching

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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 (+)

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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

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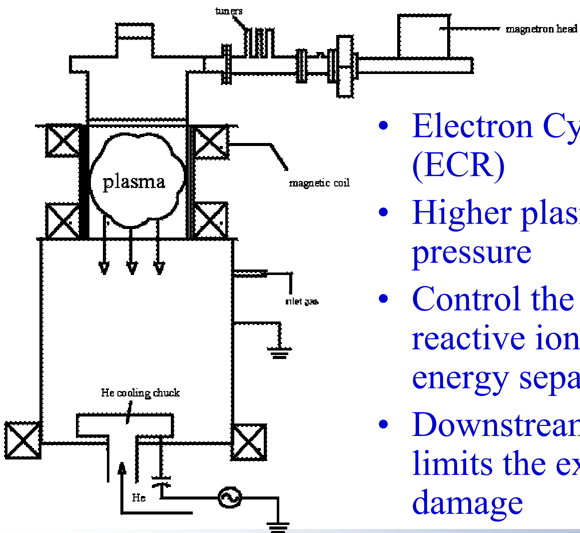
ECR Systems



- 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

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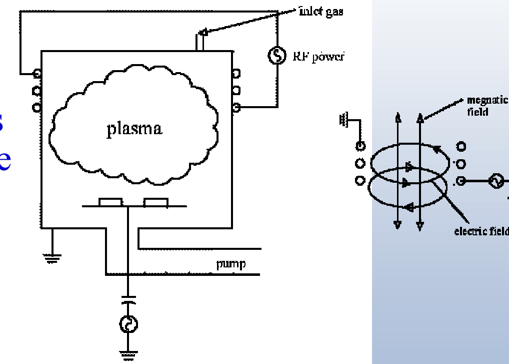
ICP System (DRIE)

- 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



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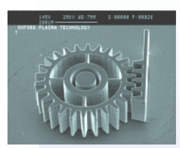
Deep Reactive Ion Etch

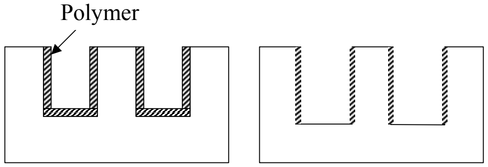


BOSCH Patent STS, Alcatel, Trion, Oxford Instruments …

Uses high density plasma to alternatively etch silicon and deposit a etch-resistant polymer on side walls

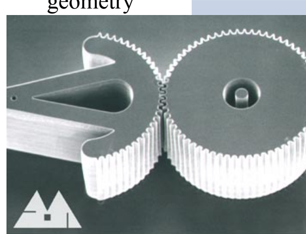
☺ Unconstrained geometry
90° side walls
High aspect ratio 1:30
Easily masked (PR, SiO2)

☹ Process recipe depends on geometry



Polymer deposition

Silicon etch using SF_6 chemistry



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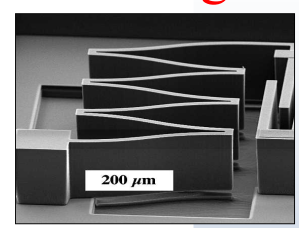
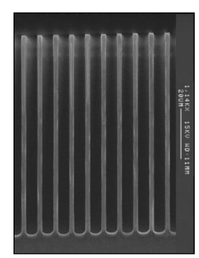
Deep Reactive Ion Etching

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

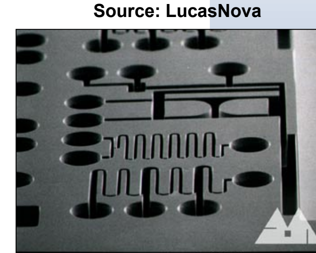


Source: LucasNova

Source: STS



Source: STS



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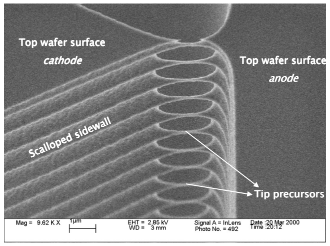
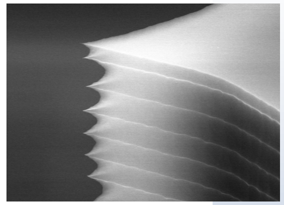
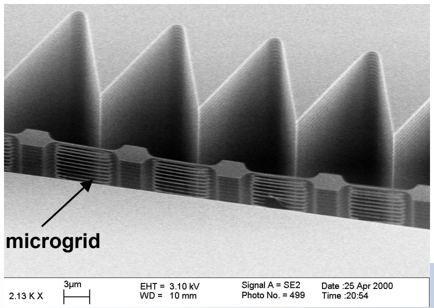
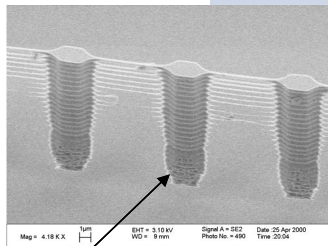
Scalloping and Footing Issues of DRIE









Footing at the bottom of device layer

Milanovic et al, IEEE TED, Jan. 2001.

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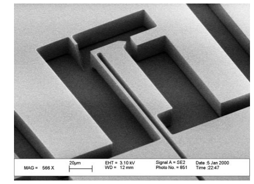
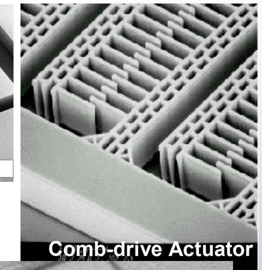
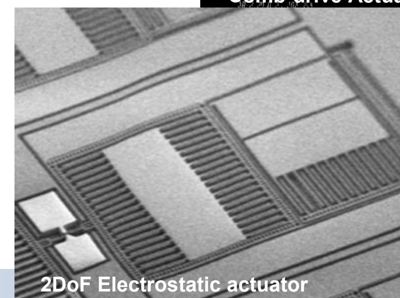
DRIE Structures

- Increased capacitance for actuation and sensing
- Low-stress structures
  - single-crystal Si only structural material
- Highly stiff in vertical direction
  - isolation of motion to wafer plane
  - flat, robust structures



Thermal Actuator





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Etch Chemistries

- Organic Films
  - Oxygen plasma is required
  - By-products: CO, CO_2, H_2O
  - Masks: Si, SiO_2, Al, or Ti
  - Addition of fluorine containing gases significantly increases etch rate but decreases selectivity (due to HF formation)

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Etch Chemistries

- Oxide and Nitride Films
  - Fluorine plasma is required (eg, CF_4)
  - Mask: PR
  - Addition of O_2
    - Increases etch rate
    - Adjusts PR : oxide and PR : nitride selectivity
- Silicon
  - Fluorine plasma (CF_4 or SF_6)
  - Chlorine plasma (Cl_2)
  - Mixed (fluorine and chlorine) plasma (Cl_2 + SF_6)

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