Clean-Room
microfabrication techniques

Francesco Rizzi
Italian Institute of Technology
Miniaturation

The first transistor
Miniaturization

The first transistor
Miniaturization

The first transistor

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Miniaturization
Moore's Law:
the number of transistors that can be placed on an integrated circuit is increasing exponentially, doubling approximately every two years.

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Microtechnology dimensions

Needs for micro-structures (100 nm – 100 μm) realization:

1. Dimensions lower than airbor particles in atmosphere.

2. Thermal expansion and humidity in atmosphere inside laboratory have a “dramatic impact” on microstructures.
Clean Room:
Laboratory where air fluxes, conditioning and filtering, building materials and operational protocols, are ruled such as “environment cleanliness” and “thermo-hygrometric parameters” are under control.
IIT Clean Room

Technical Characteristics
Controlled Temperature: 20 ± 1 °C
Humidity: 50 ± 5 %
Air changes: 10 / hr
120 m² ISO 6
300 m² ISO 7
30 m² ISO 8 (pre-chamber)

Services:
Deionized Water
Compressed Air
Nitrogen
Vacuum
Chemical benches

Ultra-pure technical gases:
Cl₂, BCl₃, SiCl₄, HBr, SiH₆Cl₂,
He, SF₆, SiH₄, NH₃, N₂O, CHF₃, CF₄,
Ar, O₂, H₂, CH₄, miscela CH₄/H₂/Ar, C₄F₈

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MOSFET realization

Fabrication process of SiC MOSFETs

1. **SiC substrate**
   - High quality SiC epitaxial layer (grown by AIST)

2. **Ion Implantation**
   - Hot implantation at 800 °C and subsequent annealing at 1650 °C in Ar

3. **Oxide formation**
   - Pyrogenic oxidation at 1100 °C using high purity H₂ and O₂

4. **Electrode evaporation**
   - Evaporation of Al electrodes

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The planar processing

Fabrication process of SiC MOSFETs

1) Material growth
   2) Ion implantation
   3) Thin Films deposition
   4) Pattern transfer

SiC substrate

High quality SiC epitaxial layer (grown by AIST)

Ion Implantation

Hot implantation at 800 °C and subsequent annealing at 1650 °C in Ar

Oxide formation

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Electrode evaporation

Evaporation of Al electrodes
The planar processing

**Fabrication process of SiC MOSFETs**

1. **SiC substrate**
   - High quality SiC epitaxial layer (grown by AIST)
2. **Ion implantation**
   - Hot oxidation at 800 °C and subsequent annealing at 1400 °C in Ar
3. **Thin Films deposition**
   - Pyrogenic oxidation at 1100 °C using high pressure of H₂ and O₂
4. **Pattern transfer**
   - Evaporation of Al electrodes

**MATERIAL PRODUCTION TECHNOLOGIES**

**MICROFABRICATION TECHNOLOGIES**

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The Microfabrication Technologies

- Optical Lithography
The Microfabrication Technologies

- Optical Lithography
- Etching of materials
**The Microfabrication Technologies**

- Optical Lithography
- Etching of materials
- Thin Films deposition methods
Optical Lithography

Reproduction of a pattern:

Expose a resist to open windows in a controlled way

The origin of the lithographic process is linked to the original process invented by Nicephore Niepce in 1826 for the photography
Optical Lithography

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Photoresist: photon sensitive polymer made of long or short chains; applied by spin coating

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Optical Lithography

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Optical Lithography

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Photoresist: photon sensitive polymer made of long or short chains

After UV light interact with polymer chain:

Positive photoresist:
Long chain molecules are broken in short chain

Negative photoresist:
Short chain molecules are joined in long chain

PAY ATTENTION: Long chain are insoluble in developer

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Optical Lithography

Reproduction of a pattern:

Expose a resist to open windows in a controlled way

UV EXPOSED PHOTORESIST

MASK MATERIAL
SUBSTRATE

DEVELOPING

POSITIVE RESIST

NEGATIVE RESIST

RESIST

RESIST

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Lithography: Critical Dimensions

- resolution limited by diffraction:
  \[ t = \sqrt{\frac{\lambda}{g}} \]
- gap minimum = resist thickness

Minimize \( t = \text{difference between real transfer image and ideal transfer image} \)

Find a tradeoff between the gap \( g \) and the diffraction peak to repeat inside the photoresist the mask pattern

Intensity \( \approx 0.5 \): minimum dose for development
Lithography: Critical Dimensions

436 nm, Hg-Xe Lamp + Optical Filter: CD ≈ 650 nm

365 nm, Hg-Xe Lamp + Optical Filter: CD ≈ 350 nm

248 nm, KrF Excimer Laser

193 nm, ArF Excimer Laser

F2: 157 nm, F2 Laser

EUV: 13.4 nm, Soft X-ray
Etching

Selective removal of thin film(s) resulting in a desired thin film(s) pattern

Etch mask
photoresist or oxide/nitride material patterned by optical lithography and resistant to the etchant agent

Etch mask

After development
Etching
Mask Removal
**Basic Concepts**

- Etching process consists of three steps:
  - Mass transport of reactants (through a boundary layer) to the surface to be etched.
  - Reaction between reactants and the film(s) to be etched at the surface.
  - Mass transport of reaction products from the surface through the boundary layer.

- Etching is usually done using liquid phase or gas phase reactants:
  - **Liquid phase (wet) etching** — reaction products soluble in solvent or gaseous.
  - **Gas phase etching** — reaction products gaseous/sublimation temperature.
**Etching figure of merit**

**Etch rate**: rate of film removal, typically 100 nm/min

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**Anisotropy**: Anisotropyic etching is the preferred process
Etching figure of merit

**Etch rate**: rate of film removal, typically 100 nm/min

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**Selectivity**: Etchant could attack substrate, not only film
Wet Etching

How?

Simply place the wafer in solution that attacks the film to be etched but not the mask (resist).

- Diffusion reactive species from the liquid bulk through the boundary layer to the surface of wafer
- Reaction of species at the surface to form solvable species
- Diffuse reaction products away from the surface through the boundary layer into the bulk of the liquid

Advantages
- High selectivity because it is based on chemical processes

Disadvantages
- Isotropic, poor process control and particulates

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Etching Chemistry

- Key ingredients in any wet etchant:
  - Oxidizer
    - examples: $\text{H}_2\text{O}_2$, $\text{HNO}_3$
  - Acid or base to dissolve oxidized surface
    - examples: $\text{H}_2\text{SO}_4$, $\text{NH}_4\text{OH}$
  - Diluent medium to transport reactants and products through
    - examples: $\text{H}_2\text{O}$, $\text{CH}_3\text{COOH}$
Drawback of Wet Etching

• Lack of anisotropy

• Poor process control

• Excessive particulate contamination

=> Wet etching used for noncritical feature sizes
Dry Etching Overview

- Feature-sizes smaller-than 1-μm cannot be well defined with isotropic wet-etching processes.
- Anisotropic-etching is necessary to form submicron-sizes.
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Critical dimension feature disappear

Dry Etching

Material removal reactions occur by a gas phase etchant.
Dry Etching Overview

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Critical dimension feature disappear

Dry Etching

Material removal reactions occur by a gas phase etchant.

- Dry-etching can be anisotropic.
- It also eliminates handling, consumption, & disposal of large quantities of dangerous acids & solvents.
• **Physical Etching**
  – *The gaseous ion, accelerated to the substrate, mechanically ejects substrate material*
  – *Highly Anisotropic*
  – *Non-Selective*
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• **Chemical Etching**
  – *Thermalized neutral gaseous radicals chemically combine with substrate material forming volatile products*
  – Highly-Selective
  – Isotropic
**Physical Etching**

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**Combination of the two**

- Ion bombardment enhances or promotes the reaction between an active species and the substrate material
- Controlled Anisotropy
- Adequate Selectivity
Plasma: the 4th state of matter

Screening potential near a point charge

Plasma particles are free to move; don’t feel each other

Plasma-solid interface

Decreasing Pressure increase

Constant potential inside the plasma; Plasma is on

Decreasing Pressure increase

Strong electric field at the boundary; Plasma is off
RF Electric field produce plasma by glow discharge. Plasma is used to crack molecules and/or drive chemical reactions useful for dry etching.

Electric potential is constant inside the bulk of plasma. The voltage drop is mostly across the sheath area, where the plasma is off, and ions are accelerated towards electrodes.

\[ RF \approx 13.56 \text{ MHz} \]
Physical Etching: the Ion Sputtering system

In this process all of the RF voltage is applied to a **smaller target electrode**. A neutral gas is injected in a **low pressure** environment.

**Glow discharge** is used to energize chemically inert ions or atoms (e.g., Ar). Atoms close to the **sheath area** are strongly accelerated bombarding the wafer.
Chemical Etching: the Plasma Etching system

The opposite of Sputtering

In this process RF voltage is applied to a separate electrode while the target electrode is grounded. A gas is injected in a high pressure environment.

Glow discharge is used to produce chemically reactive species; the sheath field tends to be negligible: radicals or ions diffuse towards the wafer with low acceleration and remove material from the substrate by chemical means.

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Combination of Physical and Chemical: the Reactive Ion Etching system

In this process all of the RF voltage is applied to a smaller target electrode; neutral gas is replaced by one or more halogen-rich chemical species at low pressure environment.

Glow discharge is used to produce chemically reactive species and chemically inert ions; neutral ions bombard the substrate surface while radicals diffuse towards the wafer with negligible acceleration and remove material from the substrate by chemical means.
High density plasma: Inductively Coupled Plasma Etching

Ions and reactive species spiral around B field in the plasma going towards the wafer; this act on the plasma density, even at low pressure, changing the sheat area.

RF voltage applied on the target electrode; RF current in the coil around the chamber induces a magnetic field in the chamber perpendicular to the target electrode.

Glow discharge is used to produce chemically reactive species and chemically inert ions; Magnetic field controls the plasma density in the chamber; Electric field controls the ion energy; Control of ion energy and ion density select and balance independently the physical and chemical mechanism for etching.
Ion Energy vs. Pressure for a Plasma

Changing pressure and RF voltage for E and B field is possible to realise the most suitable process for each fabrication need.
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Once finished the etching process, Mask etching photoresist is removed by Acetone.
Thin Film Deposition techniques

• Vacuum deposition Methods
  Ultra High Vacuum (<10^{-8} \text{ mTorr})

• Physical Deposition:
  – Material to be deposited is ready in pellet or disk
    1. Magnetron Sputtering deposition (metal, dielectrics);
    2. Thermal deposition (metal, dielectrics);
    3. Electronic beam deposition (metal);

• Chemical Deposition:
  – Material to be deposited is product of a chemical reaction
    1. Electrodeposition (metal);
    2. Chemical Vapor Deposition (CVD) (dielectrics);
Magnetron Sputtering

- Magnetic field increases plasma density and enhance the etching rate of the target material, at low pressure.
- Target material atoms deposit on the wafer placed on the opposite electrode.
Thermal Evaporation

- A resistively heated coil increases the temperature of material inside the crucible up to the sublimation point.
- Metallic or dielectric atoms evaporate towards the wafer.
**E-beam Evaporation**

- Electron gun, under the crucible, ejects an intense, high energy beam, by thermionic effect.
- The strong magnetic field bends the beam causing it to collide on the surface of the crucible, filled by metal.
- Metallic atoms evaporate towards the wafer.

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**Diagram:**
- Electron gun (E-gun)
- Filament
- Permanent Magnet
- Crucible filled of metal
- HV (High Voltage)
**Electrodeposition**

Electrodeposition is the process of coating a thin layer of one metal on top of a different metal by deposition of metallic ions in acid solution from one electrode to the opposite.
Chemical Vapor Deposition

- wafer
- susceptor
• In Chemical Vapor Deposition (CVD) the substances to be deposited (precursor) enters a chamber in a gaseous state.
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**Parameters to favor reactions if more energy is needed:**

• *Increase temperature of wafer by resistive heater inside the susceptor (LPCVD).*
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**Parameters to favor reactions if more energy is needed:**

- *Increase temperature of wafer by resistive heater inside the susceptor (LPCVD).*
- *Apply a RF voltage to create a plasma if low temperature is needed (PECVD)*
Shadow evaporation and Lift-off

*Lift off:* the process to remove the mask deposition photoresist after deposition.

*Problem:*
if there is a continuous deposition layer, it’s difficult to remove the photoresist. It’s completely covered by coating; difficult to desolve by acetone.

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As opposite of etching, we need the photoresist to give a shadow effect to ease remotion of deposited film on it. It is possible using some chemicals before development to make the unexposed photoresist stronger to development.
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**Chlorobenzene and developer**

*Hardned photoresist layer by chlorobenzene: re-entrant profile.*
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*Lift off the resist and excess metal*
[...] I would like to describe a field, in which little has been done, but in which an enormous amount can be done in principle. [...] 

What I want to talk about is the problem of manipulating and controlling things on a small scale. [...] 

Why cannot we write the entire 24 volumes of the Encyclopedia Brittanica on the head of a pin? [...] 

- Information on a small scale 
- Miniaturizing the computer 
- The marvelous biological system 
- Rearranging the atoms 
- Atoms in a small world
So, Guys, there is a plenty of job in your doctorate.

Have fun and Good luck!!!!

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