Overview

- **Thin films:**
  - Thermal Silicon Oxide
  - Silicon Dioxide (SiO₂)
  - Polysilicon
  - Silicon Nitride (Si₃N₄)
  - Phosphosilicate Glass (PSG)
  - Metal films (e.g., tungsten and aluminum)
- Thin films may be produced by:
  - Thermal oxidation
  - Physical Vapor Deposition
  - Chemical Vapor Deposition
  - Epitaxial Deposition
  - Atomic Layer Deposition (ADL)
- Ion implantation to improve electrical conductivity or to control etching characteristics.
- Wet bulk micromachining
  - Isotropic and anisotropic etching
  - 3-D structure and sacrificial layers
- Deep Reactive Ion Etching (DRIE)
- Characterization with Atomic Force Microscopy
- Substrate bonding
  - Silicon direct bonding
  - Anodic bonding
Thin-Films

- Thin-film application is an *additive* process.
- Some important thin-films are:
  - Thermal Silicon Oxide
  - Silicon Dioxide (SiO₂)
  - Polysilicon
  - Silicon Nitride (Si₃N₄)
  - Phosphosilicate Glass (PSG)
  - Metal films (e.g. tungsten and aluminum)

Thermal Silicon Oxide
- Amorphous material.
- Insulating layer.
- Mask
- Sacrificial layer.
- Impurities such as Na⁺ and K⁺ diffuse through it.
- Most dopants except Ga diffuse poorly through it.
- Thicknesses usually less than 1 µm are produced.

Silicon Dioxide (SiO₂)
- Chemical Vapor Deposition (CVD) techniques
- Insulator between conducting layers.
- Diffusion and ion implantation masks.
- Sacrificial material.

Thermal Oxide Furnace
Polysilicon Films
- Low Pressure Chemical Vapor Deposition (LPCVD).
- Initially amorphous, but may crystallize during deposition.
- Transition from small grains at the film/substrate interface to columnar crystallites on top.
- Dopants, impurities and temperature influence crystal orientation.
- Dopants decrease resistivity to produce conductors and control stress.
- Can be doped by diffusion, implantation, or by the addition of dopant gases during deposition.
- Piezoresistive sensor elements may be fabricated from polysilicon.

Silicon Nitride (Si$_3$N$_4$)
- CVD Techniques
- Amorphous
- Insulator between conducting layers.
- Excellent water and ionic barrier.
- Can not be directly put on silicon.
- May be put on a silicon dioxide layer.
- Highly selective etch rates.
- Hard material that may be used for structural purposes.
- An important mechanical membrane and isolation/buffer material.

Phosphosilicate Glass (PSG)
- PSG and borophosphosilicate glasses (BPSG) soften and flow at lower temperatures, enabling smoothing of topography.
- Etch faster than silicon dioxide, hence more suitable sacrificial layer.
- Creating by addition of phosphine to the gas steam.
- Dielectric between conducting metal layers.
- Getting and flow capabilities.
- Passivation coat to provide mechanical protection
**Metal Films**
- CVD and PVD techniques.
- Aluminum and tungsten are commonly used.
- Metals with high reflectivity include Al (aluminum) and Au (gold).
- Metals with high mass density include W (tungsten), Au (gold) and Pt (platinum).
- Metals with specific adsorption and adhesion characteristics include Pd (palladium), Ir (iridium), Au (gold) and Pt (platinum).
- Tungsten will nucleate on silicon or metal surfaces, but not on dielectrics such as oxides and nitrides.

**Thin-Film Deposition Processes**

**Physical Vapor Deposition**
- Material is transported in vapor form from a source to a substrate through a vacuum or low-pressure gaseous environment:
  - Evaporation,
  - Sputtering,
  - Arc vapor deposition
  - Laser ablation,
  - Ion plating.

**Chemical Vapor Deposition**
- Chemical vapor deposition is the deposition of a solid on a heated surface from a chemical reaction in the vapor phase.

**Epitaxial Deposition**
- A single crystal layer can be deposited onto the surface of a substrate wafer.

**Thermal Evaporation**

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*Steven S. Saliterman*
Chemical vapor deposition is the deposition of a solid on a heated surface from a chemical reaction in the vapor phase. Like PVD, the deposition species are atoms or molecules or a combination of these.

Advantages & disadvantages
LPCVD

Loading the LPCVD

CVD Process

SiO₂ can be deposited with CVD by reacting silane and oxygen in a LPCVD reactor as shown:
\[
\text{SiH}_4 + O_2 \rightarrow \text{SiO}_2 + 2\text{H}_2
\]
SiO₂ can be deposited with LPCVD by decomposing tetra-ethyl-ortho-silicate, Si(OC₂H₅)₄, also known as TEOS. This is vaporized from a liquid source.

SiO₂ can also be deposited with LPCVD using dichlorosilane:
\[
\text{SiCl}_2\text{H}_2 + 2\text{H}_2\text{O} \rightarrow \text{SiO}_2 + 2\text{H}_2 + 2\text{HCl}
\]
Si₃N₄ can be deposited with LPCVD using dichlorosilane and ammonia:
\[
3\text{SiCl}_2\text{H}_2 + 4\text{NH}_3 \rightarrow \text{Si}_3\text{N}_4 + 6\text{HCl} + 6\text{H}_2
\]

There are three factors that control the nature and properties of the deposit:
- Epitaxy
- Gas-phase precipitation
- Thermal expansion
CVD structure can be controlled by manipulation of temperature, pressure, supersaturation and the CVD reaction.
Ceramics, including SiO₂, Al₂O₃, Si₃N₄ and most dielectrics are amorphous.
Metal deposits tend to be crystalline.
Materials That Can Be Deposited

- **Oxides:** Al₂O₃, HfO₂, SiO₂, TiO₂, SrTiO₃, Ta₂O₅, Gd₂O₃, ZrO₂, Ga₂O₃, V₂O₅, Co₂O₃, ZnO, ZrO:Al, ZnO:B, In₂O₃:H, WO₃, MoO₃, Nb₂O₅, NiO, MgO, RuO₂
- **Fluorides:** MgF₂, AlF₃
- **Organic-hybrid materials:** Alucone
- **Nitrides:** TiN, TaN, Si₃N₄, AlN, GaN, WN, HN, NbN, GdN, VN, ZrN
- ** Metals:** Pt, Ru, Pd, Ni, W
- **Sulfides:** ZnS

Select ALD Features

- 100% film density guarantees ideal material properties.
- Insensitive to dust (grows underneath dust!).
- Oxides, nitrides, metals, semiconductors possible (Cambridge Nanotech provides standard recipes).
- Amorphous or crystalline depending on substrate and temperature.
**ALD Features**

- Digital thickness control to atomic level (no rate monitor needed, just set the number of atomic layers).
- Perfect 3D conformality, 100% step coverage: uniform coatings on flat, inside porous and around particle samples.
- Low defect density.
- Gentle deposition process for sensitive substrates, no plasma.
- Low temperature deposition possible (RT-400°C).
- Low stress because of molecular self assembly.

**Ion Implantation**

1. In ion implantation, the dopant element is ionized, accelerated to a kinetic energy of several hundred keV, and then driven into the substrate.
2. The electrical conductivity of an intrinsic semiconductor can be increased through doping. The charge carrier density can be increased through impurities of either higher or lower valence.
3. Doping can be used to control etching by reducing etch rates.
4. Sources for n-type doping include antimony, arsenic and phosphorous; and for p-type doping, boron.

**Controlled Etching**

- **Anisotropic etchants** (potassium hydroxide, ethylene diamine pyrochatehol, and tetramethyl ammonium hydroxide):
  - Etch silicon preferentially along preferred crystallographic directions.
  - Show a reduction of etch rate in heavily doped p-type regions.
- **Boron** typically is incorporated using ion implantation for this purpose.
Wet Bulk Surface Micromachining

- In wet bulk micromachining features are sculptured in bulk materials like silicon, quartz, sapphire, ceramics, SiC, GaAs, InP and Ge by orientation independent (isotropic) or orientation-dependent (anisotropic) wet etchants.
- Integrated circuits typically have aspect ratios of 1-2, while in BioMEMS the ratio may be up to 400.

Orientation is important because of different characteristics and etching speeds in different planes, and resulting etching angles.
- The (111) plane has the highest atom packing density and is relatively non-etching compared to the others.
- The angles between planes, (100) and (110) are 45 or 90 degrees, between (100) and (111) are 54.74 degrees, and between (111) and (110) planes 35.26, 90 or 144.74 degrees.

Recall Silicon Crystal Orientation

Isotropic vs. Anisotropic Etching
Isotropic Etching Agents

- Isotropic etchants are usually acidic, and lead to rounded features (HNA = HF (hydrofluoric acid) + HNO₃ (nitric acid) + CH₃COOH (acetic acid)):

\[
\text{Si} + 6\text{HF} \rightarrow \text{H}_2\text{SiF}_6 + 3\text{H}_2\text{O} + \text{H}_2
\]

\[\text{H}_2\text{SiF}_6 \text{ is water soluble}\]

Anisotropic Etching Agents

- Anisotropically etchants are alkaline:

\[
\text{Si} + 2\text{OH}^- \rightarrow \text{Si(OH)}_2^{2+} + 4e^-
\]

\[
4\text{H}_2\text{O} + 4e^- \rightarrow 4\text{OH}^- + 2\text{H}_2
\]

\[
\text{Si(OH)}_2^{2+} + 4\text{OH}^- \rightarrow \text{SiO}_2(\text{OH})_2^{2-} + 2\text{H}_2\text{O}
\]

\[
\therefore \text{Si} + 2\text{OH}^- + 2\text{H}_2\text{O} \rightarrow \text{Si(OH)}_2^{2+} + 2\text{H}_2
\]
**Structural Elements**

- Common structural elements include **polysilicon**, **polyimide**, **silicon nitride**, and **tungsten**.
- The **polysilicon** and its sacrificial layer, **silicon dioxide**, can be applied by LPCVD. Silicon dioxide can be etched away with **hydrofluoric acid (HF)** solution without etching the polysilicon.
- **Polyimide** can be used with **aluminum** as the sacrificial layer, the latter being dissolvable with **acid-based etchants**.
- **Silicon nitride** is both a good structural material and electrical insulator. **Polysilicon** can be used as the sacrificial layer, in which case **KOH** and **EDP** can be used as the etchants.
- **Tungsten** can be applied by CVD over **silicon dioxide**, and again HF is a suitable etchant to remove the silicon dioxide sacrificial layer.

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**Stiction and Critical Point Drying**

- Sulfur hexafluoride (SF$_6$) is flowed during the etching cycle and octafluorocyclobutane (C$_8$F$_8$) during the sidewall protection cycle.

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**Deep Reactive Ion Etching (DRIE)**

- Sulfur hexafluoride (SF$_6$) is flowed during the etching cycle and octafluorocyclobutane (C$_8$F$_8$) during the sidewall protection cycle.
Atomic Force Microscopy

Substrate Bonding
- Silicon Direct Bonding
  - Silicon to Silicon
  - Silicon on Insulator (SOI)
- Anodic Bonding
  - Silicon to Glass (Pyrex 7740)
- Intermediate Adhesive Layers
- Lasers

Anodic Bonder
Summary

- Important thin-films include:
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