N-type Transistor

- Poly Gate
- Gate Oxide
- Diffusion

\[ V_{ds} \]
\[ +V_{gs} \]
\[ i \] electrons

Diffusion Mask

- Mask for just the diffused regions

Polysilicon Mask

- Mask for just the polysilicon areas

Top view shows patterns that make up the transistor
Combine the two masks

- You get an N-type transistor
- There are other steps in the process...

IC Fabrication

- IC fabrication is very similar to screenprinting...
  - Image is created (positive or mask)
  - Exposed onto a screen (photo emulsion)
  - Unexposed parts are washed away
  - Remainder is used as a mask (stencil) for the processing (application of ink)

Screen Printing

- Like Screenprinting
  - At a much finer scale of course...
    - Start with a mask that defines where the processing should happen at each step (for each color)
    - Expose mask onto photoresist (emulsion)
    - Wash away unexposed parts
    - Use hardened polymer as a mask for processing

Screen Printing

- Multiple masks (separations) are used to make multi-color images
- Processing order is important
The first step is to grow a very thin insulating layer of silicon dioxide (yellow layer) on the entire surface of the pure silicon wafer by exposing it to extreme heat in an atmosphere of pure oxygen.

Next, a thin layer of aluminum (gray layer) is applied by vacuum metallization directly on top of the silicon dioxide layer. This material will ultimately become the “silicon seascape”.

A thin film of photore sist (blue layer) is applied to the surface of the entire wafer, which is then spun at high speed to evenly spread the viscous fluid-like photore sist across the surface.

A mask containing the pattern of the sailboat, the sun, and a seagull is then placed over the wafer and ultraviolet light is then passed through the pattern exposing the soft photore sist beneath.

The soft unexposed photore sist is removed with an organic solvent leaving only those areas that were hardened by exposure to the ultraviolet light. An outline of the seascape is now in place.

The exposed areas of aluminum metal are now removed by “etching” the surface of the wafer in a process called ion beam milling that removes the unprotected aluminum.
The hardened photoresist is then removed by washing with acid and the seascape is finished. We can now photograph it through a microscope and add it to the gallery in the Silicon Zoo.

Look at Inverter Layout Again

- How many layers?
- How many processing steps?

A Cutaway View

- CMOS structure with both transistor types

Figure 3.4 Subwavelength features printed with and without OPC. Predistortion of corners in OPC reduces undesired rounding. (Adapted from Scheltenberg98 with permission of SPIE.)

Figure 1.34 Inverter cross-section with well and substrate contacts. Color version on inside front cover.

Figure 1.35 Inverter mask set. Color version on inside front cover.
Growing the Silicon Crystal

- Need single crystal structure
  - Single crystal vs. Polycrystalline silicon (Poly)

Czochralski Method

- Need single-crystal silicon to accept impurities correctly
  - Donor elements provide electrons
  - Acceptor elements provide holes
- Pull a single crystal of silicon from a puddle of molten polycrystalline silicon

Slice Crystal into Wafers

- Slice into thin wafers (.25mm - 1.0mm), and polish to remove all scratches

Lapping and Polishing

Oxidation, Growing SiO2

- Essential property of silicon is a nice, easily grown, insulating layer of SiO2
  - Use for insulating gates (“thin oxide”)
  - Also for “field oxide” to isolate devices
Making the Mask

Adding Photoresist

“Steppers” Expose the Mask

Develop and Bake Photoresist

Now Etch the SiO₂

Add a Processing Step

- Photoresist can be positive or negative
  - Does the exposed part turn hard, or the unexposed part?

- Use very short wavelength UV light
  - Single frequency, 436 - 248 nm
  - Expensive! ~$5,000,000/machine...

- Developed photoresist is soft, unexposed is hardened
  - So you can etch away the soft (exposed) part

- Etch the SiO₂ to expose the wafer for processing
  - Then Spin Rinse, and Dry

- Now that we’ve got a pattern etched to the right level, we can process the silicon
- Could be:
  - Ion Implantation (i.e. diffusion)
  - Chemical Vapor Deposition (silicide, Poly, insulating layers, etc.)
  - Metal deposition (evaporation or sputtering)
  - Copper deposition (very tricky)
Ion Implantation

- Implant ions into the silicon
  - Donor or Acceptor

Chemical Vapor Deposition

Metal Deposition

- Typically aluminum, gold, tungsten, or alloys

Advanced Metalization

Copper is Tricky

- 40% less resistance than Aluminum
  - 15% system speed increase
- But, copper diffuses into Silicon and changes the electrical properties
**Ashing - Removing Photoresist**

A Plasma Asher (Fusion Systems)

**Final Layer: Passivation**

- Basically a final insulating layer (SiO2 or Si3N4) to protect the circuit

**CMOS Fabrication**

- Start from single-crystal silicon wafer
- Use photolithography to pattern device layers
  - Essentially one mask/photolithographic sequence per layer
  - Built (roughly) from the bottom up
    - 6 - Metal 3
    - 5 - Metal 2
    - 4 - Metal 1
    - 2 - Polysilicon
    - 3 - Diffusions
    - 1 Tub (N-well)

**Self-Aligned Gates**

- Thinox in active regions, thick elsewhere
- Deposit Polysilicon
- Etch thinox from active region (Poly serves as mask for etch/diffusion)
- Implant dopant

**CMOS Inverter**

- CMOS Inverter
This two-inverter circuit (of Figure 3.25 in Rabaey’s text) will be manufactured in a twin-well process.

Starting wafer: n-type with doping level $= 10^{13}/\text{cm}^3$

* Cross-sections will be shown along vertical line A-A’
N-well Construction

1. Oxidize wafer
2. Deposit silicon nitride
3. Deposit photoresist
4. Expose resist using n-well mask
5. Develop resist
6. Etch nitride and
7. Grow thick oxide
8. Implant n-dopants (phosphorus) (up to 1.5 µm deep)

P-well Construction

Repeat previous steps

Grow Gate Oxide

0.055 µm thin
Grow Thick Field Oxide

- 0.9 $\mu$m thick
- Uses Active Area mask
- Is followed by threshold-adjusting implants

Polysilicon layer

Source-Drain Implants

- n+ source-drain implant (using n+ select mask)
- p+ source-drain implant (using p+ select mask)

Contact-Hole Definition

1. Deposit inter-level dielectric (SiO$_2$) -- 0.75 $\mu$m
2. Define contact opening using contact mask

Aluminum-1 Layer

- Aluminum evaporated (0.8 $\mu$m thick)
- Followed by other metal layers and glass