CS/ECE 5710/6710

CMOS Processing

YouTube…

- Global Foundries: https://www.youtube.com/watch?v=UvluuAliA50
- Philips: https://www.youtube.com/watch?v=35jWSQXku74
- Intel: http://newsroom.intel.com/docs/DOC-2476
- Fairchild (ancient history – 1967!): https://www.youtube.com/watch?v=z47Gv2cdFtA
N-type Transistor

Poly Gate
Gate Oxide
Diffusion

Drain
Source
N+
N+
P-doped substrate

G +Vgs
G S Vds i electrons

FIGURE 3.1 IBM, East Fishkill, NY fab (Courtesy of International Business Machines Corporation. Unauthorized use not permitted.)
N-type from the top

- Top view shows patterns that make up the transistor

Diffusion Mask

- Mask for just the diffused regions
Polysilicon Mask

- Mask for just the polysilicon areas

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
IC Fabrication

- 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
Photolithographic Process

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.
Photolithographic Process

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".

Photolithographic Process

A thin film of photoresist (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 photoresist 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 photoresist beneath.

The soft unexposed photoresist 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

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**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.

**FIGURE 1.36** Cross-sections while manufacturing the n-well.
FIGURE 1.37 Cross-sections while manufacturing polysilicon and n-diffusion.

FIGURE 3.9 Gate and shallow source/drain definition.
Figure 1.38 Cross-sections while manufacturing p-diffusion, contacts, and metal.

Figure 3.10 Transistor with LDD and deep diffusion, salicide, and planarized dielectric.
FIGURE 3.11 Aluminum metallization

FIGURE 3.12 Partially completed 6-transistor SRAM array using local interconnect
(Courtesy of International Business Machines Corporation. Unauthorized use not permitted.)
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

Silicon wafer after processing
Lapping and Polishing

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

Oxidation, Growing SiO2

Oxidation Furnace
(Silicon Valley Group - Thermco Systems)
Making the Mask

Adding Photoresist

Photoresist can be positive or negative

- Does the exposed part turn hard, or the unexposed part?
“Steppers” Expose the Mask

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

Develop and Bake Photoresist

- Developed photoresist is soft, unexposed is hardened
  - So you can etch away the soft (exposed) part
Now Etch the SiO2

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

Add a Processing Step

- 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

- CVD Tool (Applied Materials)
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

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)

Exception

Contact

Via

Via

FIGURE 3.38 Hand-drawn layout: (a) standard cell, (b) cutting patterns onto ruby lith (Reprinted from [Volk01] with permission of Intel Corporation.)

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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
Metal Mask

Other Cutaway Views

- Polysilicon
- Al
- SiO₂
- p-substrate
- n⁺-well
- p⁻-substrate
Another View of Fab

- Taken from slides by Jan Rabaey
- From his text “Digital Integrated Circuits”

Circuit Under Design

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

Start Material

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
N-well Construction

(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

- Uses Active Area mask
- Is followed by threshold-adjusting implants
- 0.9 µm thick

Polysilicon layer
Source-Drain Implants

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

Source-Drain Implants

p+ source-drain implant (using p+ select mask)
Contact-Hole Definition

(1) Deposit inter-level dielectric (SiO$_2$) — 0.75 µm

(2) Define contact opening using contact mask

Aluminum-1 Layer

Aluminum evaporated (0.8 µm thick) followed by other metal layers and glass