Conductors:
characterized by loosely bound electrons that can easily move throughout the material, allowing current flow; e.g. copper, silver, aluminimum

Insulators:
tightly bound electrons that resist movement, resulting in a poor conductor, e.g. rubber, glass

Semiconductors:
bridge the gap btwn. conductors & insulators. their conductivity can be controlled

Importance:
allow precise controll of currents, helps build electronic comps. such as:

Transistors.
fundamental building block of modern electronics, acting as switches & amplifiers

Integrated Circuits (ICs):
combine multiple transistors & other comps. on a single chip - cores of microprocessors

Light-emitting diodes (LEDs):
convert electrical energy into light, used in displays & lighting application

Silicon
Advantages:
- Abundant (2nd) & Earth-friendly
- Building Blocks & Protection
  → acts as protection to shield delicate comp. as an insul.
- Tailoring Conductivity
  → controlled via doping; introduce specific impurities

Types of Semiconductor

Intrinsic Semiconductors: The Natural State
- pure semiconducting mat. (single atom species)
- e.g. Si & Ge (Germanium)
- show intrinsic electrical props. w/o intentional impurities
- natural state: a specific energy band structure allowing moderate conductivity

Extrinsic Semiconductors: Doping Adds New Possibilities
- intentionally modified by introducing impurity atoms via doping, which can alter mat.'s electrical props.
- 2 common types:

p-type semiconductors:
doped w/ elements that create holes in the valence band → (+) charge carriers

n-type semiconductors
doped w/ elements that introduce extra electrons → (-) charge carriers

Silicon Wafer:
single-crystal slices of silicon w/ precise thickness & orientation & are substrates for microelectronics
→ microchips, solar cells, transistors, & diodes
- recyclable & energy efficient

Silicon Ingot Production
The Czochralski Method:
creates a solid, single-crystal structure from molten Si

Process:
1. A seed crystal (small Si crystal) dipped into a molten silicon melt & is slowly pulled out while rotating
2. Silicon atoms attach to the ascending seed & grow as a single crystal

Advantages: high-yield, cost-effective, large-scale

Wafer Slicing & Polishing
Ingots are cut into thin wafers using diamond saws & polished to achieve uniform thickness & flatness

Wafer Cleaning & Inspection

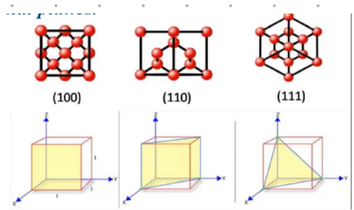
Chemical Cleaning Methods:
Wafers are immersed in chemical solutions (e.g. acids, bases, or solvents) that effectively remove organic & inorganic contaminants

Mechanical Cleaning Methods:
Ultrasonic cleaning exposes wafers to high frequency soundwaves that dislodge contaminents

Quality Control
automated optical & laser-based systems detect defects, scratches, or irregularities; metrology tools are used to measure thickness & surface roughness to ensure reproducibility.

Crystal Structure of Silicon Wafers

Si atoms are arranged in a diamond cubic lattice; each atom bonds w/ 4 neighboring atoms.



Anisotropy:
different crystallographic planes have varying properties

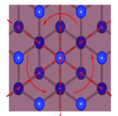
Dopant Diffusion:
dopants (e.g. boron, phosphorus) diffuse diff. along crystal axes

Etching Selectivity:
etchants preferentially attack specific crystal planes

- Crystal orientation affects electrical behav. (impact electrical props.)
- Carrier mobility: electrons & holes move faster along certain crystal directions
- Threshold Voltage: varies based on orientation
- Transistor Performance: Anistropy influences transistor characteristics

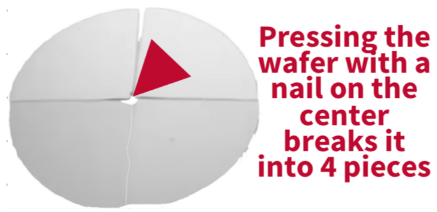
Orientation

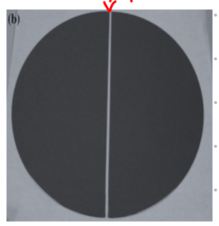
<1, 0, 0> Orientation:
- AKA "wafer flat" orientation
- The surface aligns w/ Si lattice
    - (atoms lie in square grid)
- Commonly used for CMOS (Complementary Metal-Oxide-Semiconductor)
- Anistropic props. allow provision of better transistor perform. control



How <1, 0, 0> break:
"cleavage planes" are lines of weakness along which the crystal can easily fracture; 1 set of these planes is parallel to the wafer surface
→ mortar joints btwn bricks

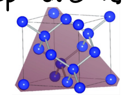
atomically perfect



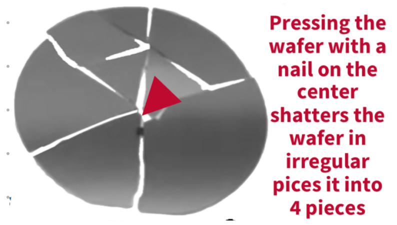


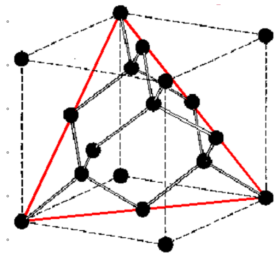
<1, 1, 1> Orientation:
- The surface aligns w/ Si lattice
    - (atoms form an equilateral triangle)
- For applications req. high mobility of electrons; e.g. RF devices
- Unique electrical prop. due to its symmetry

How <1,1,1> break:



Cleavage planes are NOT parallel to wafer structure but angled through the wafer; pyramid sides w/in.
→ break into many unpredictable fragments when stressed as the crack propagates along multiple cleavage planes
→ a challenge, but proper dicing allows exploit. of 111 wafers





Dicing Si Wafers

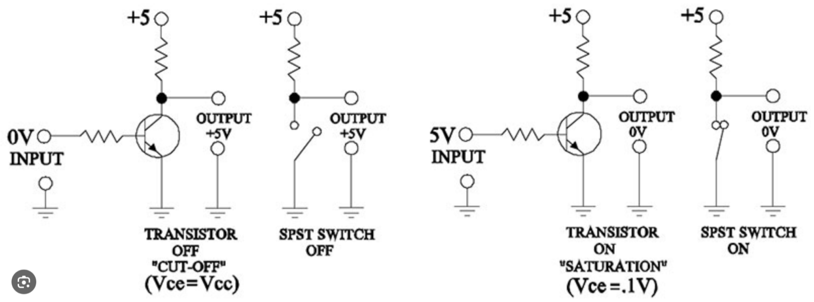
Utilizes a very thin, high-speed, diamond-coated blade to cut wafers precisely; water / coolant is sprayed during the process to minimize dust, heat, & blade wear
"Manhattan line" on wafer surface

Introduction to Transistors:

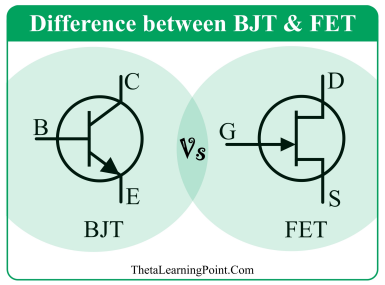
transistors act as a switch, an amplifier, or a signal modulator; it manages current flow & manipulate signals

Importance: replaced bulky vacuum tubes; enabled miniaturization, improve efficiency, & enhance performance

- Acts as switches that control current flow based on a voltage applied to their control terminal (base)
- Binary input & output:
  logic gate deal w/ binary data
  → high voltage (often 5V) = logical 1
  → low voltage (often ground 0V) = logical 0



- No voltage to base ⇨ "off", open circuit, blocking current flow
- Voltage to base ⇨ "On" (saturation mode), current flows btwn. collector & emitter



BJT: small I regulates a large I.

FET: small V regulates a large I.

Basic Principles of Transistors

Energy Bands & Band Gaps:
available energy states form bands due to the proximity of energy levels

Valence Band:
contains electrons that are tightly bonded to atoms; not free to move & contribute to stability.

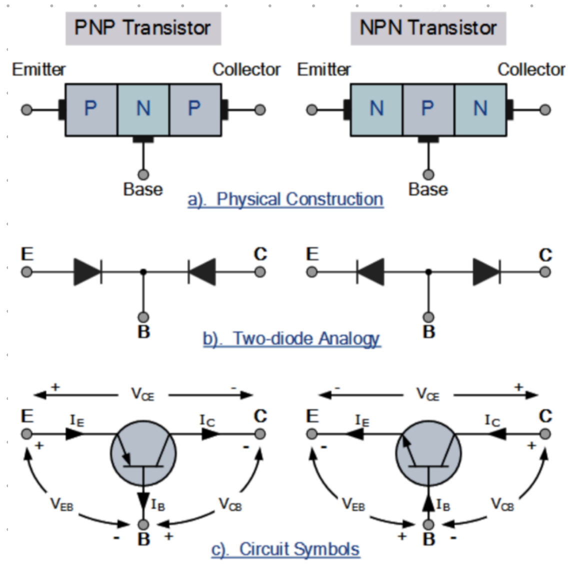
Conduction Band:
electrons have higher energy & are able to move freely within the mat.

V.B. ⇨ e⁻ ⇨ C.B., becomes mobile & can participate electrical conduction

Band Gap:
space btwn V.B. & C.B.; energy range where no electrons can exist; size varies by mat. & influences its prop.

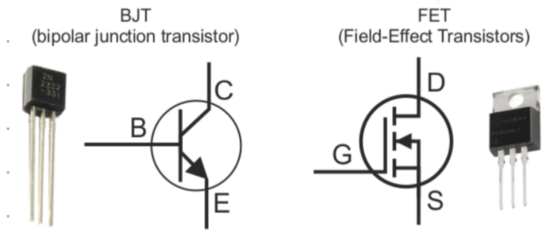
Types of Transistors

Bipolar Junction Transistors (BJTs).
Three-layer semiconductor devices w/ PNP or NPN config.
- → operate by controlling flow of current through base region, influencing the collector-emitter current
- → commonly used for amplification & switch applications



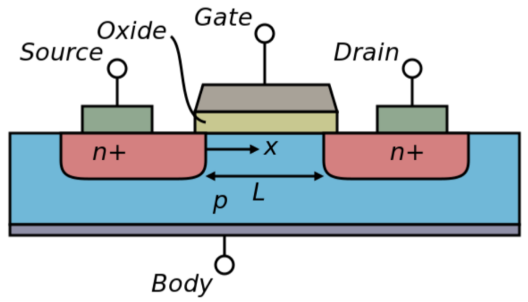
Field-Effect Transistors (FETs).
Voltage-controlled devices that regulate current flow based on an applied $\vec{E}$; 3 types:

Metal-Oxide-Semiconductor FETs (MOSFETs):
widely used in digital circuits; can be enhanced-mode or depletion-mode



Junction FETs (JFETs):
utilize a PN junction to control current; commonly used in low-noise amplifiers

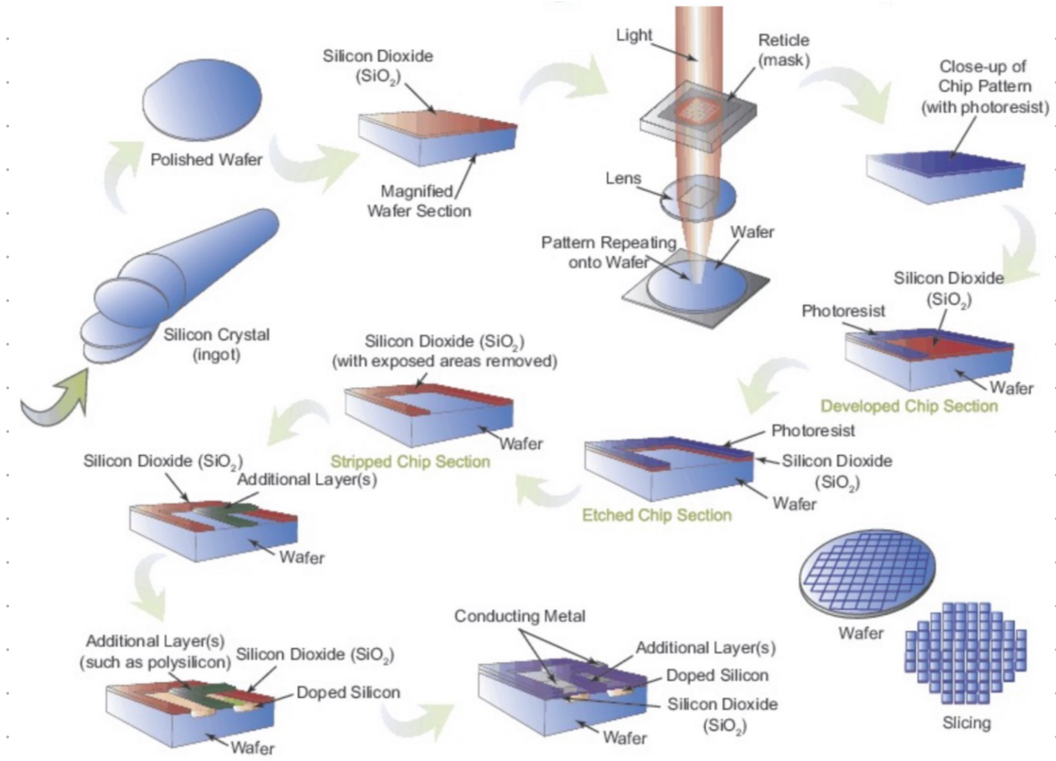
Insulated-Gate Bipolar Transistors (IGBTs):
combines features of BJTs & MOSFETs; used in power electronics.



Fabrication of Transistors & Integrated Circuits:
Wafer Mfg. ⇨ Oxidation ⇨ Lithography ⇨ Etching

⇨ Ion Implementation & Deposition ⇨ Metallization

⇨ Testing & Packaging



Cleanroom Requirements: particle free
Controls:

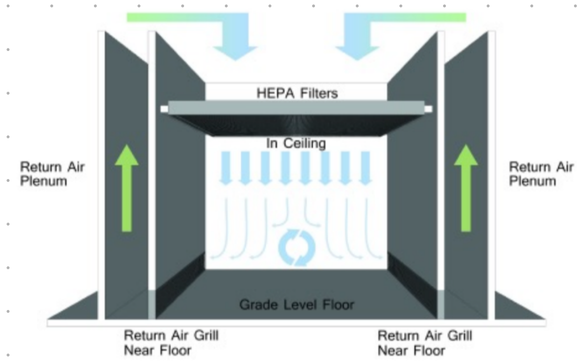
Temperature & Humidity
prevent warping of wafers & ensure consistent process behav.

Air Quality
stringent filtration systems to remove dust particles, airborne molecules, & even bacteria

Special Suits
AKA bunny suits made of lint-free materials to prevent shedding of hair, skin flakes, & clothing fibers.

Air Filtration
Multistage fitration systems including High-Efficiency Particulate Air (HEPA) filters, which removes particles as small as 0.1 micrometers from air.

Regular Cleaning & Monitoring
continuous cleaning protocols ensure dust & contaminant removal



Oxidation: Silicon Dioxide & Its Properties

Excellent Insulator high bandgap → effective electrical insulator helps prevent unwanted current flow.

Chemical Stability: resists corrosion & degradation from various chemicals & processes

Good Thermal Stability: withstand high temp. in some fabrication steps

Relatively Good Growth Uniformity: across the wafer, ensuring consistent electrical properties

Growing the Oxide Layer:

Wet Oxidation:
traditional method utilizes water vapor @ high temp. (900 ~ 1100°c) to oxidize exposed silicon:

$$Si + 2H_2O \rightarrow SiO_2 + 2H_2$$

Dry Oxidation:
uses molecular oxygen (O_2) at lower temps. (700 ~ 900°c) to achieve oxidation

$$Si + O_2 \rightarrow SiO_2$$

Silicon Dioxide · Roles in Transistors

Gate Oxide

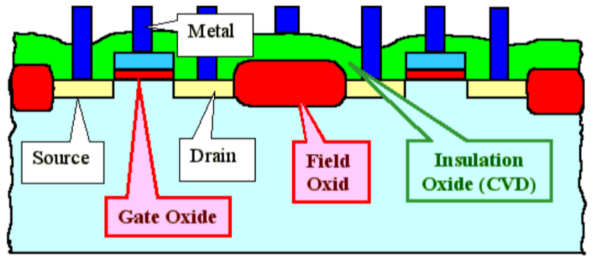
a thin layer of SiO_2 grown on the silicon substrate to act as the gate insulator in a transistor; isolates gate electrode from channel region, controlling current.

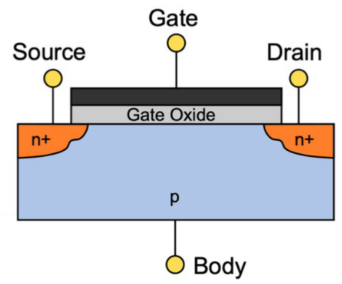
Field Oxide

thicker layers of SiO_2 used to isolate diff. transistors & other circuit elements on wafer, preventing electrical interaction & ensuring proper circuit operation.

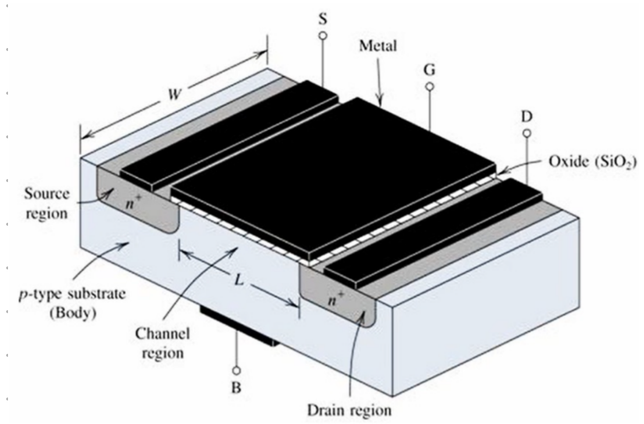
Passivation Layer

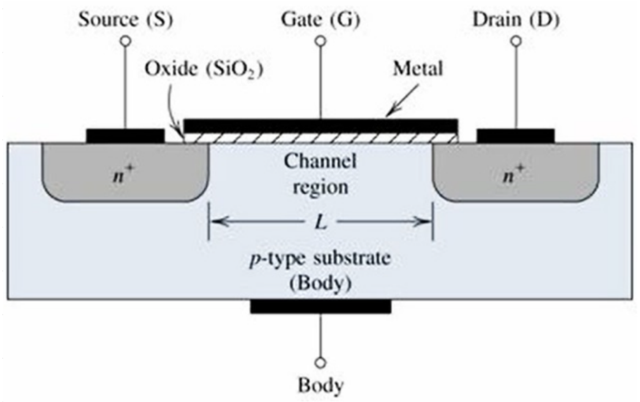
thin layer of SiO_2 deposited to protect underlying silicon surface from contaminants & improve device reliability.





NPN Field Effect Transistors:



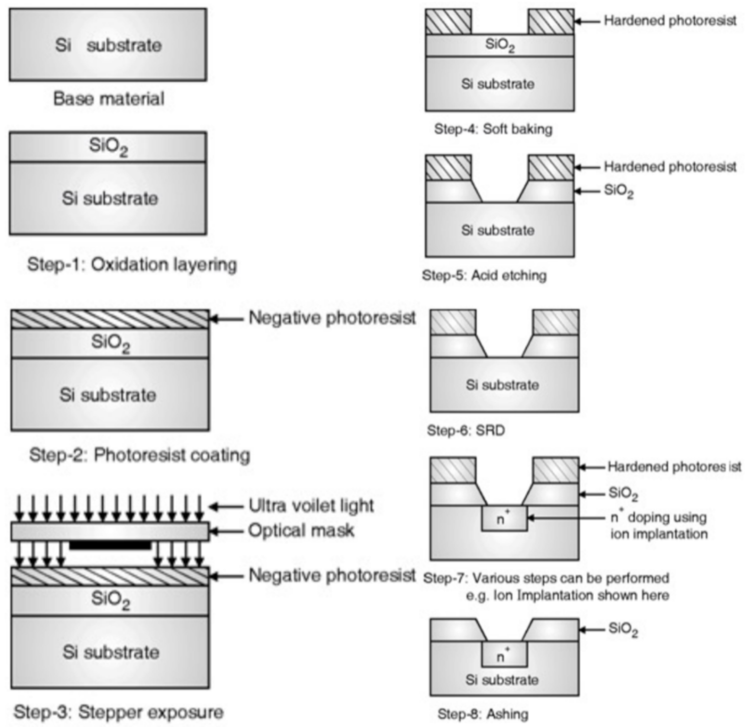


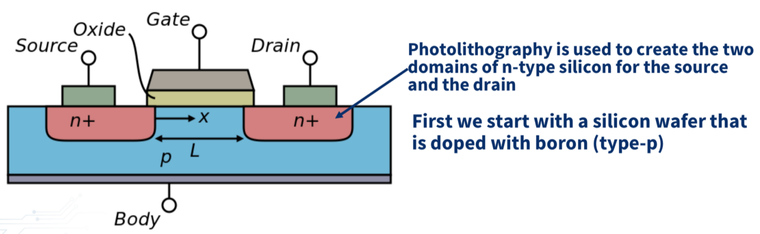
SiO_2 layer prevents gate electrode from shortcircuiting source & drain.

V_{gate} modulates the width of the channel between the source & the drain, changing I_{SD}

How To Fabricate a NPN Transistors:

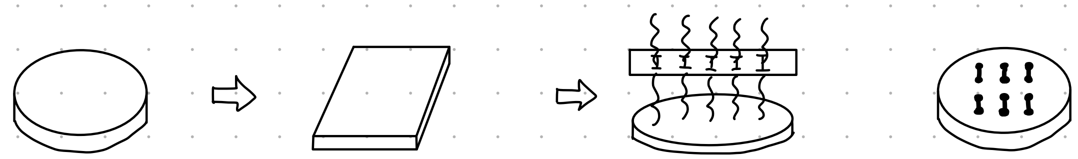
- Start w/ a silicon wafer type-p (doped w/ Boron; has 3 valence e^-)
- Create two type-n domains one for the source, one for the drain; done by creating two openings on a layer of SiO_2 via photolithography SiO_2 layer AKA implantation layer
- Photolithography used again to achieve metal deposition of source/drain/gate





Photolithography

enables the transfer of intricate circuit designs onto silicon wafers w/ high precision; utilizes light-sensitive materials & a series of step to create a patterned resist layer that guides the subsequent processes like oxid. & etch.



Silicon Wafer

Photomask / Reticle
(glass/mylar mask w/ opaque film)

Exposure
mask aligner used to pass DUV/EUV through mask onto wafer

Development
exposed resist is washed away while unexposed resist remains

Photoresist Application

- apply a thin layer of photoresist, a light-sensitive polymer onto wafer
- different types of photoresist have varying sensitivities to specific wavelengths of light
  - → positive resists become more soluble upon exposure
  - → negative resists become less soluble upon exposure
  - → choice depends on desired pattern transfer & subsequent processing steps

Photoresist Application Technique

Spin Coating

most common method; wafer spun at high speeds while the photoresist is dispensed onto the center. Centrifugal forces distributes the resist uniformly, creating a thin film w/ a consistent thickness across the wafer surface

Spray Coating