

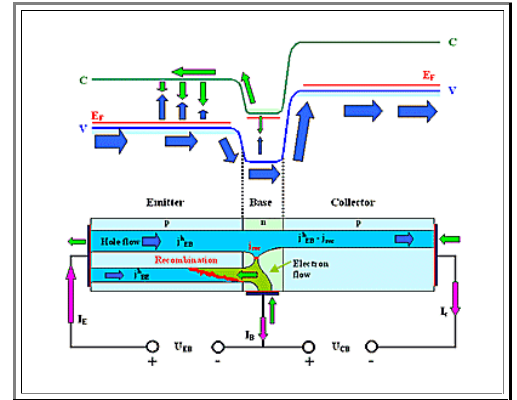
## 5.5.1 Summary: General Aspects of Silicon Technology

Essentials of the bipolar transistor:

- High emitter doping ( $N_{Don}$  for npn transistor here) in comparison to base doping  $N_{Ac}$  for large current amplification factor  $\gamma = I_C/I_B$ .
- $N_{Don}/N_{Ac} \approx \kappa = \text{injection ratio}$ .

$$\gamma \approx \frac{N_{Don}}{N_{Ac}} \cdot \left( 1 - \frac{d_{base}}{L} \right)$$

- Small base width  $d_{base}$  (relative to diffusion length  $L$ ) for large current amplification.
- Not as easy to make as the band-diagram suggests!

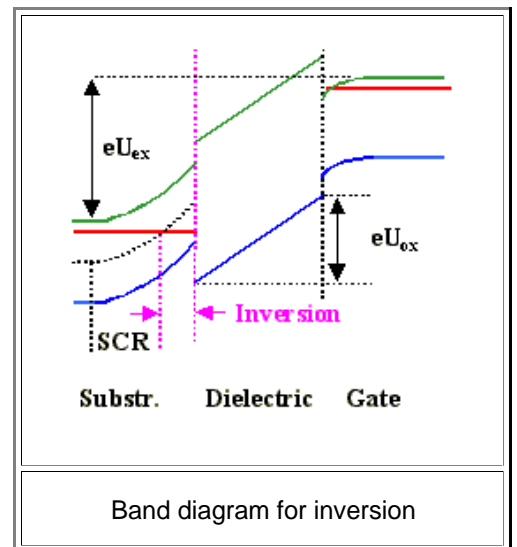
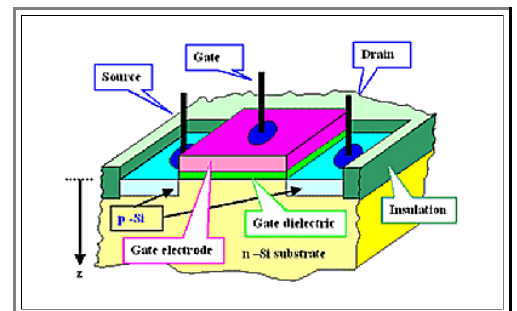


Essentials of the MOS transistor:

- Gate voltage enables Source-Drain current
- Essential process. Inversion of majority carrier type in channel below gate by:
  - Drive intrinsic majority carriers into bulk by gate voltage with same sign as majority carriers.
  - Reduced majority concentration  $n_{maj}$  below gate increases minority carrier concentration  $n_{min}$  via mass action law

$$n_{maj} \cdot n_{min} = n_i^2$$

- An inversion channel with  $n_{min} > n_{maj}$  develops below the gate as soon as threshold voltage  $U_{Th}$  is reached.
- Current now can flow because the reversely biased pn-junction between either source or drain and the region below the gate has disappeared.



The decisive material is the gate dielectric (usually  $\text{SiO}_2$ ). Basic requirement is:

- High capacity  $C_G$  of the gate electrode - gate dielectric - Si capacitor = high charge  $Q_G$  on electrodes = strong band bending = low threshold voltages  $U_G$
- It follows:

- Gate dielectric thickness  $d_{Di} \Rightarrow$  High breakdown field strength  $U_{Bd}$
- Large dielectric constant  $\epsilon_r$
- No interface states.
- Good adhesion, easy to make / deposit, easy to structure, small leakage currents, ...

$$Q_G = C_G \cdot U_G$$

Example:

$$U = 5 \text{ V}, d_{Di} = 5 \text{ nm} \Rightarrow E = U/d_{Di} = 10^7 \text{ V/cm} !!$$

$$\epsilon_r(\text{SiO}_2) = 3.9$$

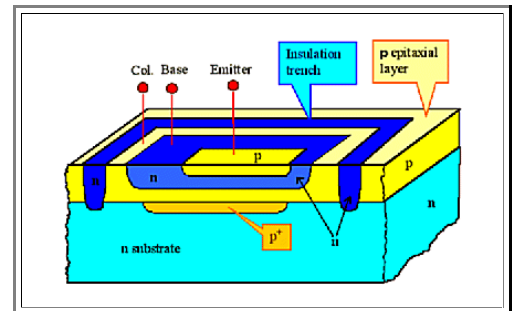
Integration means:

1. Produce a large number (up to **1.000.000.000**) of transistors (bipolar or **MOS**) and other electronic elements on a **cm<sup>2</sup>** of **Si**
2. Keep those elements electrically insulated from each other.
3. Connect those elements in a meaningful way to produce a system / product.

An integrated bipolar transistor does not resemble the textbook picture at all, but looks far more complicated  $\Rightarrow$ .

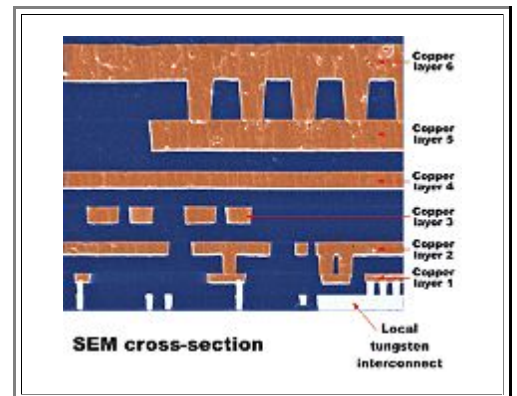
- This is due to the insulation requirements, the process requirements, and the need to interconnect as efficiently as possible.
- The epitaxial layer cuts down on the number of critical diffusions, makes insulation easier, and allows a "buried contact" structure.

**It ain't easy!**



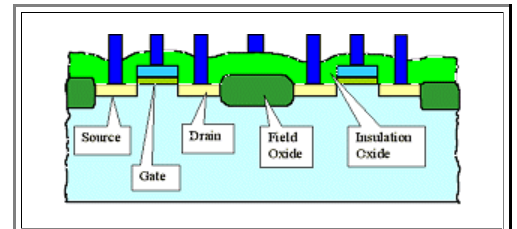
Connecting transistor / elements is complicated; it has to be done on several levels

- Materials used are **Al** ("old"), **Cu** ("new"), **W**, (highly doped) poly-**Si** as well as various silicides.
- Essential properties are the conductivity  $\sigma$  of the conductor, the dielectric constant  $\epsilon_r$  of the intermetal dielectric, and the resulting time constant  $\tau = \sigma \cdot \epsilon_r$  that defines the maximum signal transmission frequency through the conducting line.



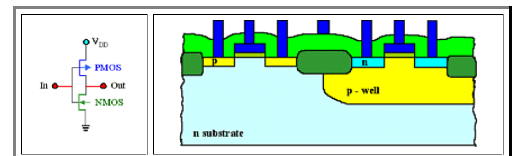
Integrating **MOS** transistors requires special measures for insulation (e.g. a field oxide) and for gate oxide production

- Since a **MOS** transistor contains intrinsically a capacitor (the gate "stack"), the technology can be used to produce capacitors, too.



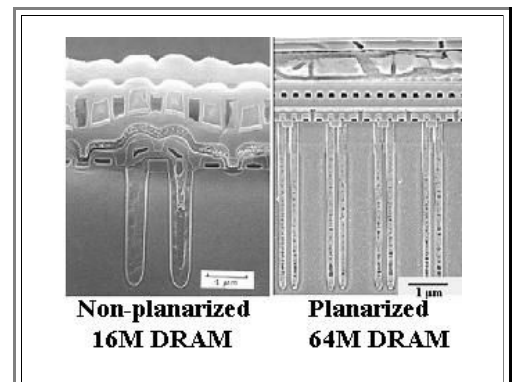
**CMOS** allows to reduce power consumption dramatically.

- The process, however, is more complex: Wells with different doping type need to be made.



Using the third dimension (depth / height) might become necessary for integrating "large" structures into a small projected area (example: trench capacitor in **DRAMs**  $\Rightarrow$ ).

- Unwanted "topology", however, makes integration more difficult.
- Planarized technologies are a must since about 1995!  $\Rightarrow$



It ain't neither easy nor cheap!

Property	Number
Feature size	0,2 $\mu\text{m}$
No. metallization levels	4 - 7
No. components	$> 6 \cdot 10^8$ (Memory)
Complexity	$> 500$ Process steps
Cost (development and 1 factory)	ca. \$ $6 \cdot 10^9$

Typical wafer size for new factories (2007) : **300 mm** diameter, **775  $\mu\text{m}$**  thickness, flatness in lower  $\mu\text{m}$  region

- Chip size a few  $\text{cm}^2$ , much smaller if possible
- Yield  $Y$  = most important parameter in chip production = % of chips on a wafer that function (= can be sold).
- $Y = 29\%$  is a good value for starting production

Chip making = running about **20** times (roughly!!) through "materials" - "structuring" loop.

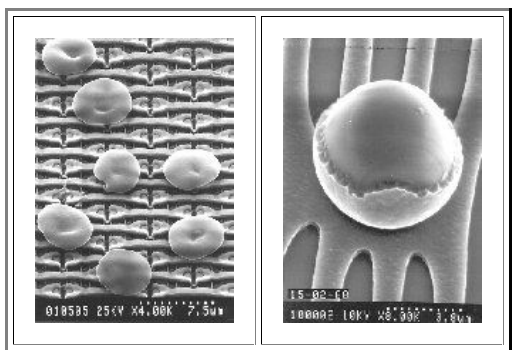
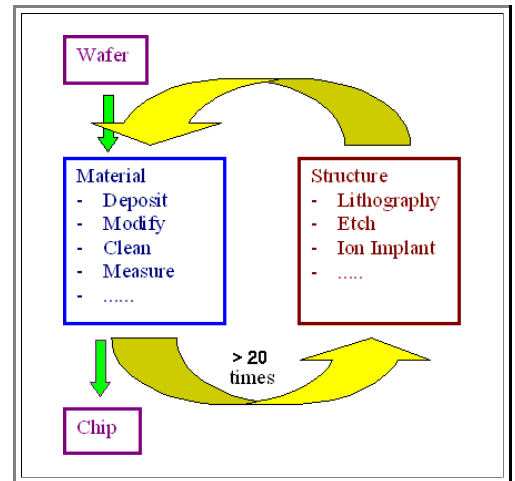
- About **400 - 600** individual processing steps (= in / out of special "machine") before chip is finished on wafer
- More than **30** processing steps for packaging (after separation of chips by cutting)
- Simple estimate: **99.9%** perfection for each processing step means  $Y < 70\%$ .

Dirt in any form - as "particles" on the surface of wafer, or as "contamination" inside the wafer is almost always deadly

- Particles with sized not much smaller than minimum feature sizes (i.e.  **$< 10\text{ nm}$**  in **2007**) will invariably cover structures and lead to local dysfunction of a transistor or whatever.
- Point defects like metal atoms in the **Si** lattice may precipitate and cause local short circuits etc. from the "inside", killing transistors
- One dysfunctional transistor out of **1.000.000.000** or so is enough to kill a chip!

Being extremely clean is absolutely mandatory for high Yields  $Y$ !

- Use cleanrooms and hyper-clean materials!
- It won't be cheap!



- Moore's law predicts exponentially growth of "chip complexity" with a high growth rate - how far will it reach?
- Problems and costs are growing exponentially with every new generation.
- It follows: The market must grow exponentially too, if you want to make a profit.
- It follows: Large amounts of money can be easily made - or lost.
- Falling behind the competition in your technology and yields means certain death for companies without a monopoly in some product.

## Questionnaire

Multiple Choice questions to all of 5

