Doping.Epitaxy

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Chapters 6, 14, 15

Previous lecture

- Oxidation
- Lab device
- Bonding and CMP are left

Outline

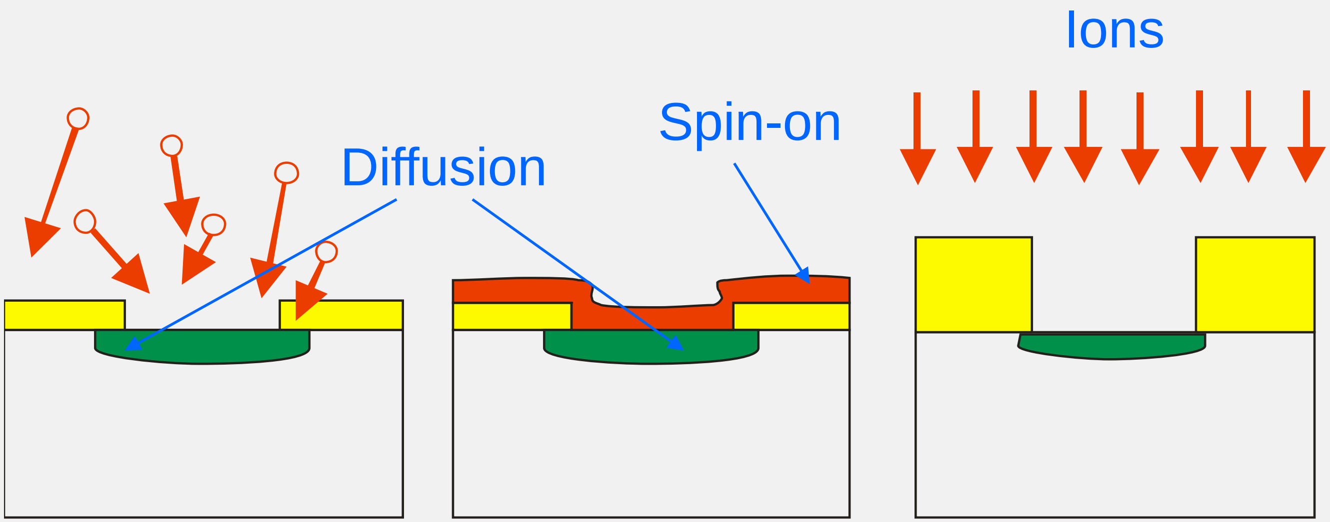
- Selective doping
- Diffusion
- Implantation
- Epitaxy

Types of doping

- Uniform doping
  - – during crystal growth (doped raw Si)
  - – during epitaxy (gas containing dopant)

- Selective doping
  - – by ion implantation
  - – by diffusion

Selective doping by phosphorus



Gas phase doping
Oxide as a mask
e.g. $POCl_3$ as a source
1000ºC
Lateral spread = depth

Solid-source doping
Oxide as a mask
e.g. P_2O_5 as a source
1000ºC
Lateral spread = depth

Ion implantation
Photoresist as a mask
Accelerated P^+ as a source
Room temperature?
Lateral spread = 1/3 depth

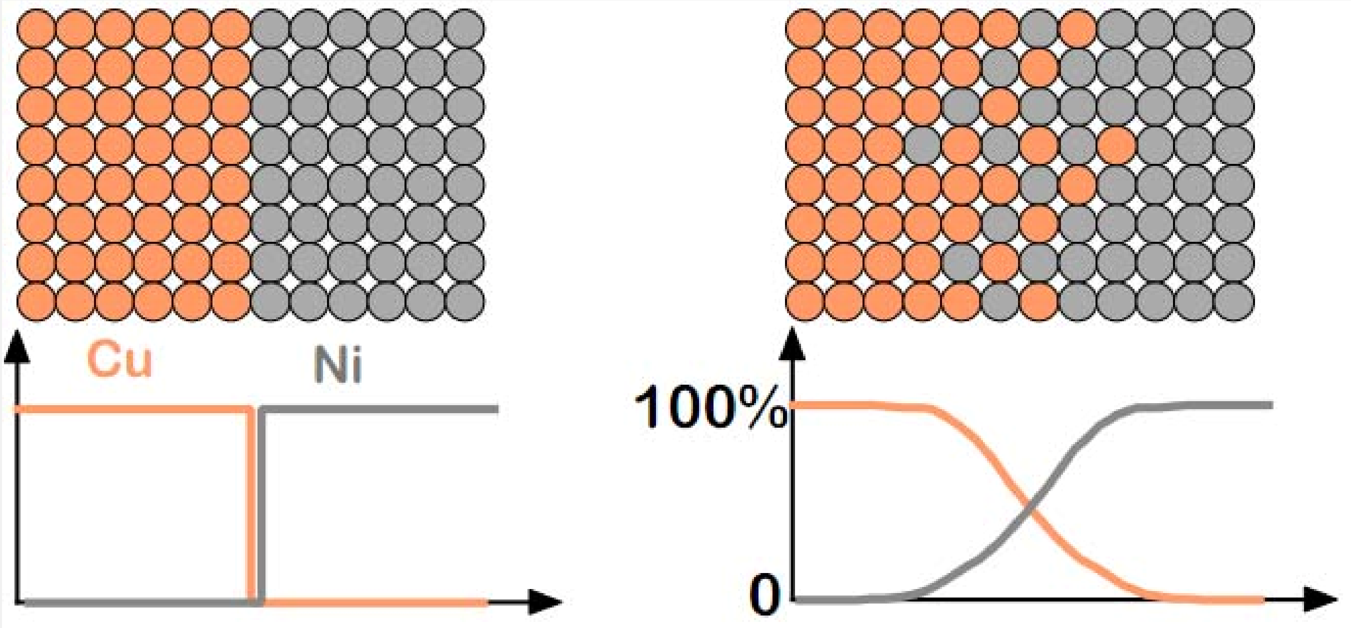
Diffusion definition

Diffusion is the movement of foreign, or impurity atoms with respect to the atoms of the host crystal along concentration gradient

Initially

After some time and non-zero temperature

100%

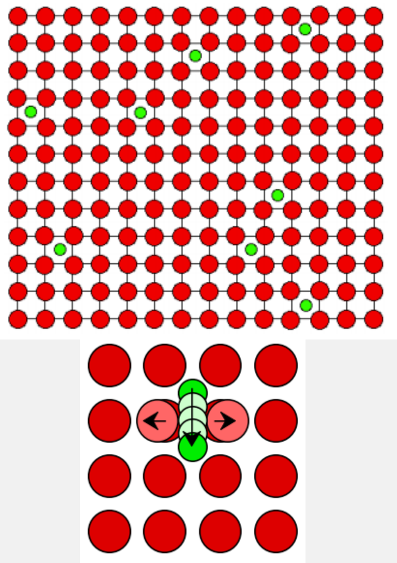


Concentration profile

Concentration profile

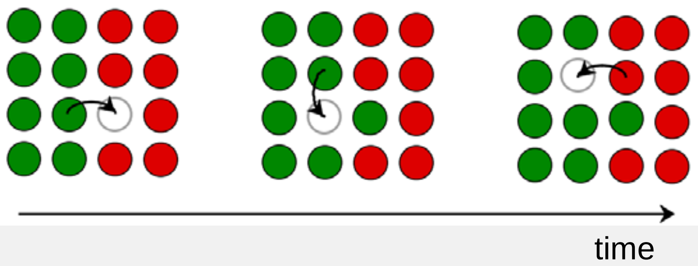
Diffusion mechanisms

Interstitial



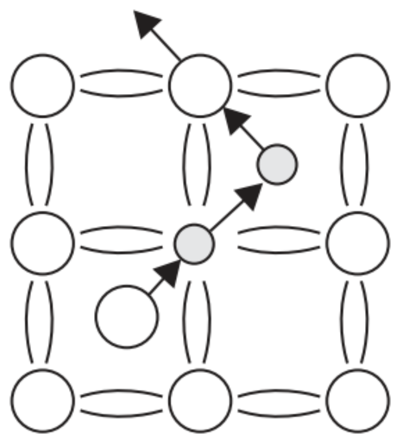
E_a = 1-1.5 eV

Substitutional
As, Sb



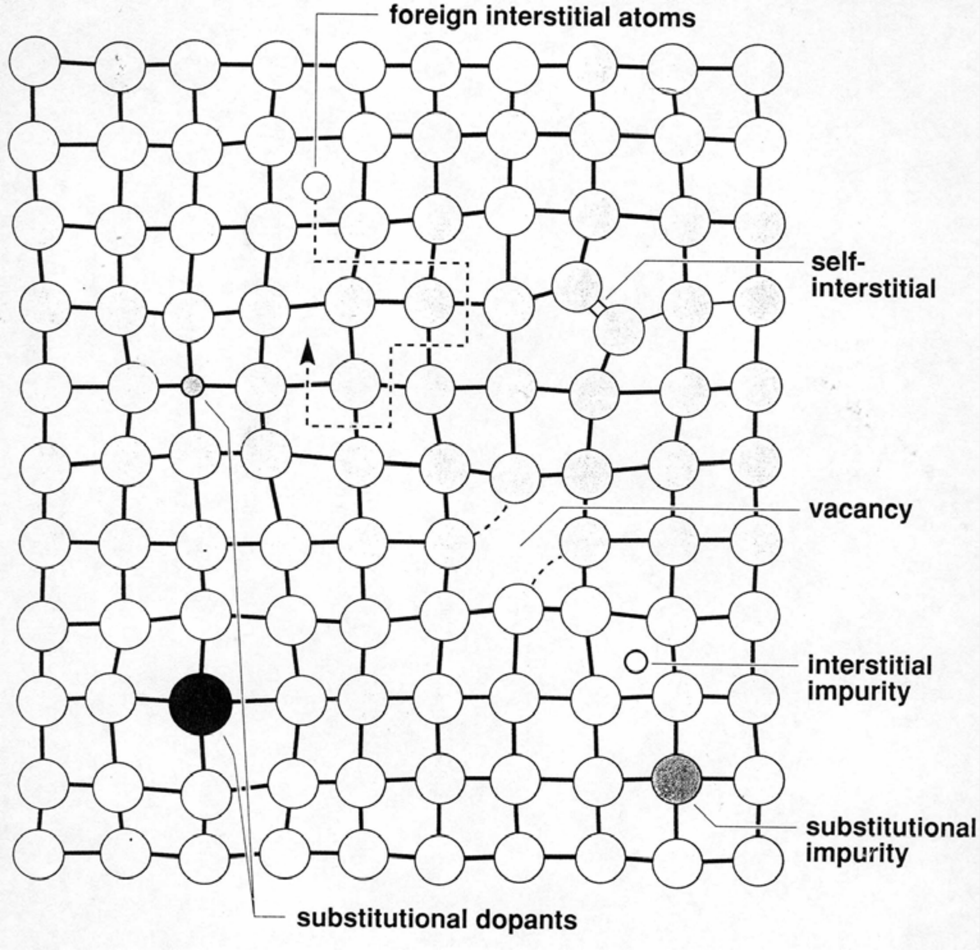
E_a = 3.5-4 eV

Interstitialcy
B, P



E_a = 3.5-4 eV

Dot lattice imperfection – possible diffusion ways



Fick's first law

- Diffusion flux, atoms/(s·cm^2)

$$j = -D\left(\frac{\partial N}{\partial x}\right)$$

- where *D* is the diffusion coefficient (cm^2/s), *N* is concentration (cm^{-3}).
- Diffusion coefficient can be presented by

$$D = D_0 e^{\boxed{-\frac{E_a}{kT}}}$$

- D_o is the frequency factor
- E_a is the activation energy
- *k* is Boltzman's constant, $k = 1.38*10^{-23}$ J/K
- *T* is temperature in Kelvin

Charachteristic diffusion length

$$x \approx \sqrt{4Dt}$$

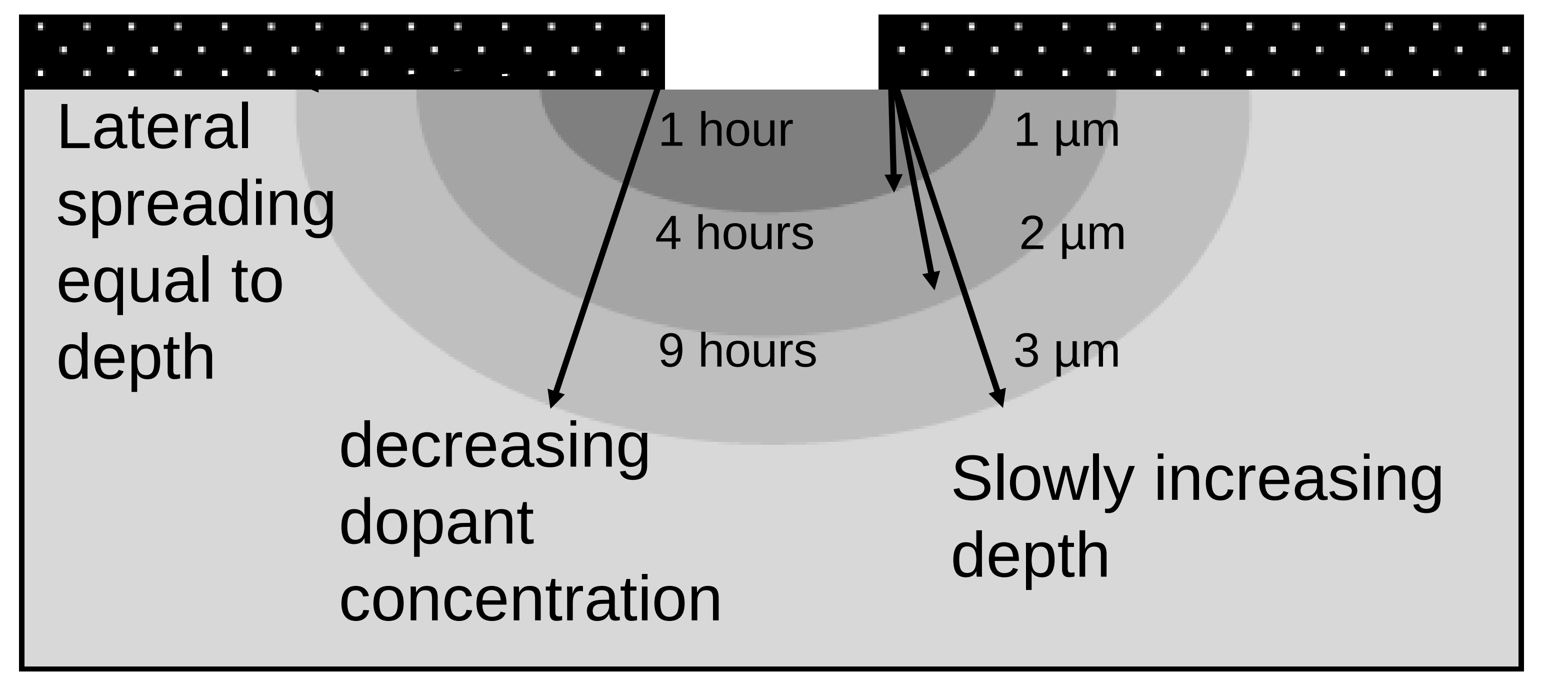
For boron at 950 °C $D = 4 \times 10^{-15}$ cm^2/s

at 1050 °C $D = 4.7 \times 10^{-14}$ cm^2/s.

$x = 0.26$ µm for one hour at 1050 °C

	Boron	**Phosphorous**
D_o (cm^2/s)	0.76	3.85
E_a (eV)	3.46	3.66

Time evolution of diffusion depth: $x \approx \sqrt{Dt}$



Lateral spreading equal to depth

decreasing dopant concentration

Slowly increasing depth

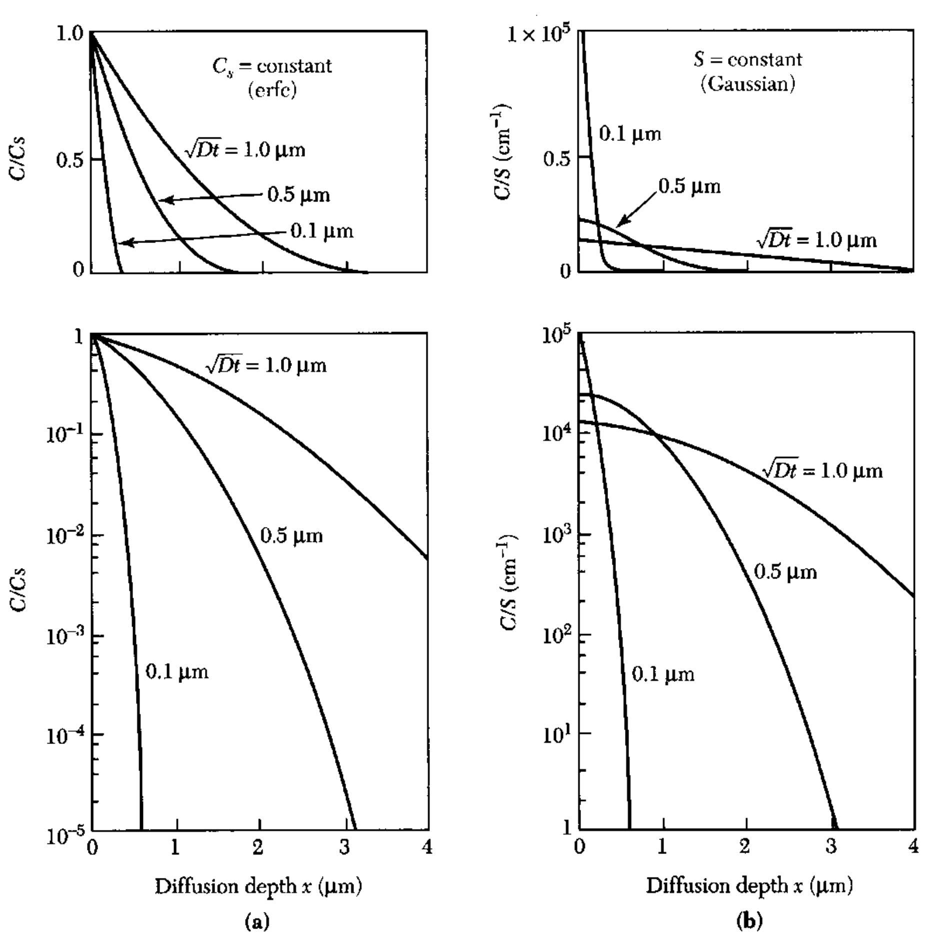
Diffusion profiles

Infinite source

Limited source or Drive-in

Linear

Logarithmic



Realization

- Diffusion happens in oxidation furnaces
- Always O_2 is added to a doping gas, i.e diffusion is connected with Si oxidation
- In case of several diffusions, the 1-st one must be with highest temperature (the deepest one)
- Diffusion areas are invisible
- Sheet resistance decreases after doping

Mask thickness for selective diffusion

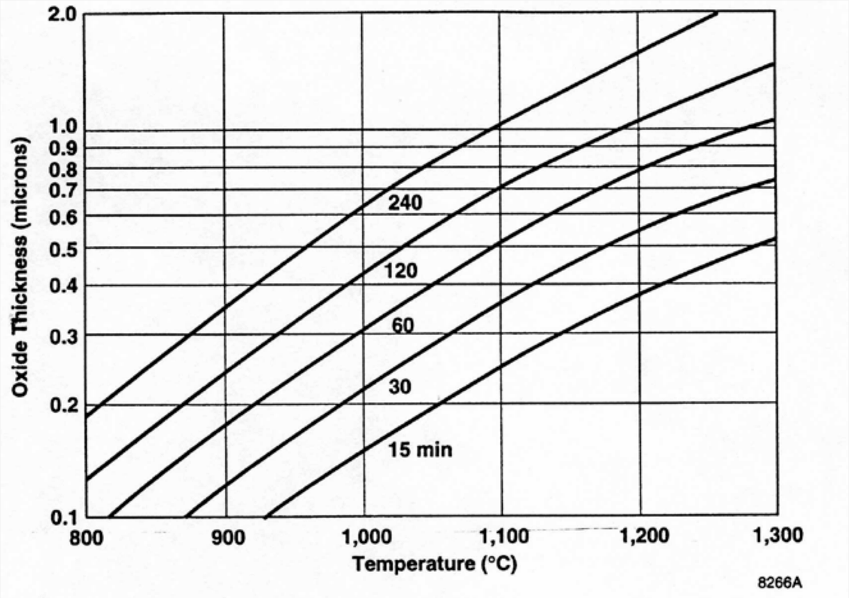


Figure 4-19. Oxide Thickness Required to Mask Against Phosphorus Diffusion.

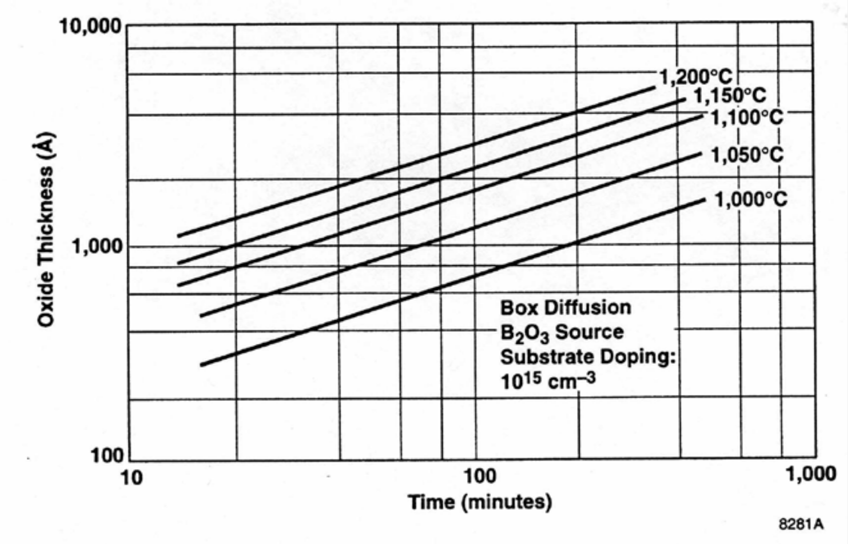
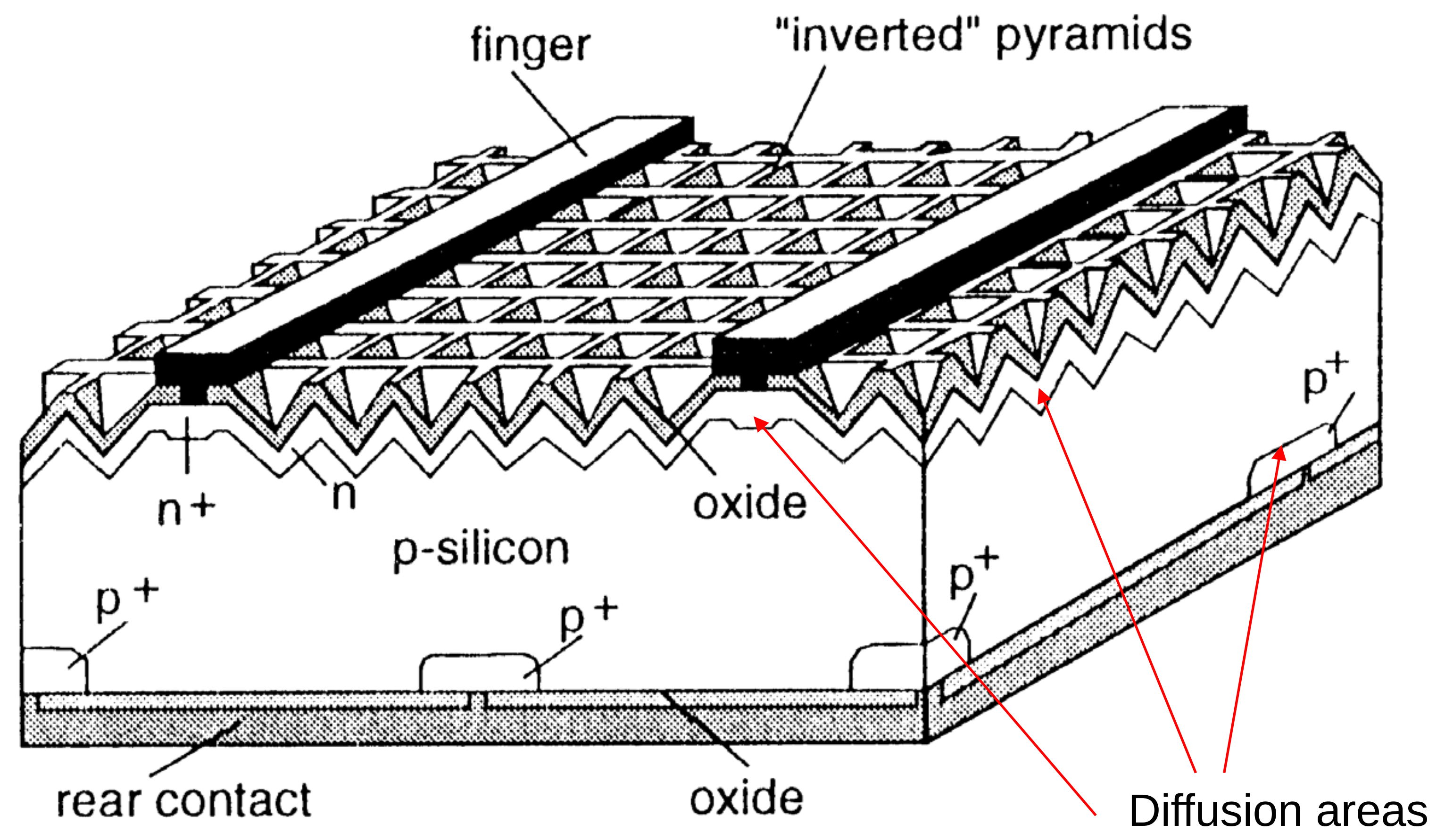


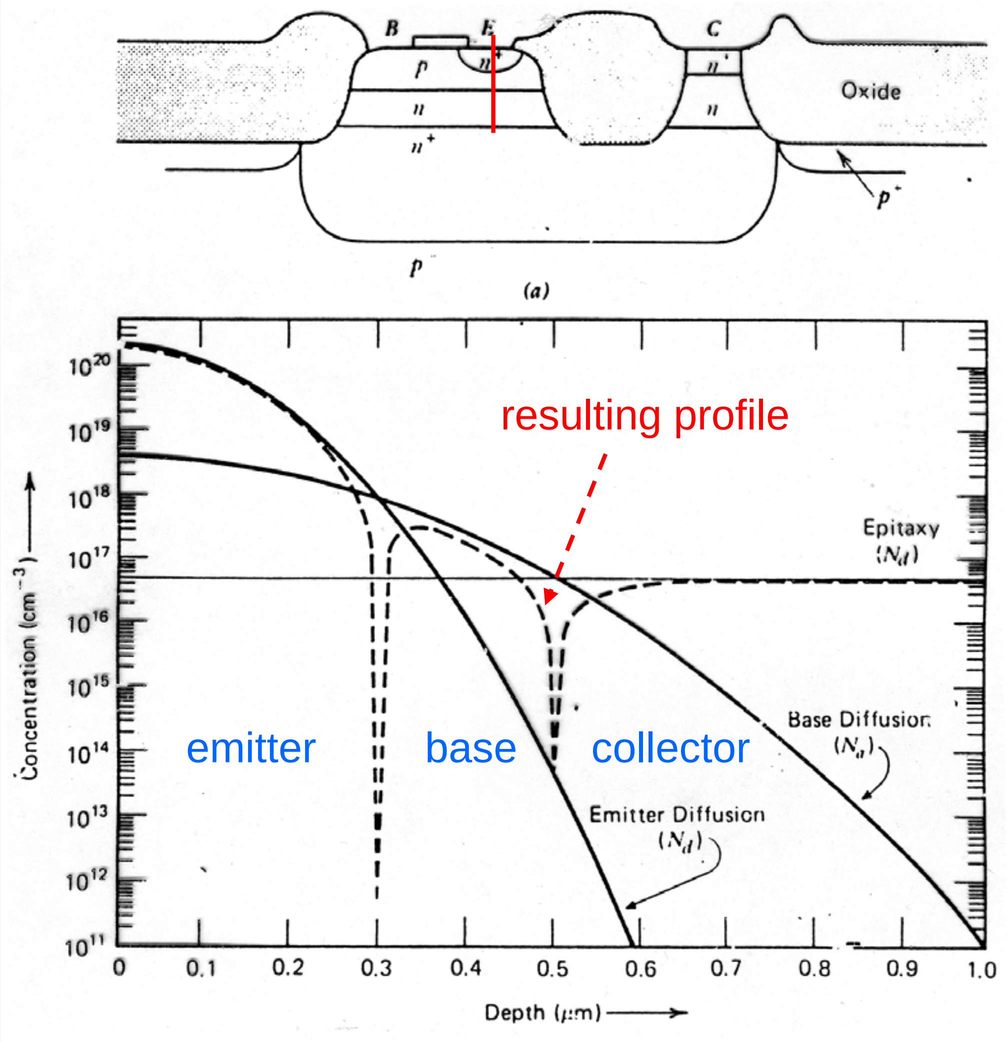
Figure 4-20. Oxide Thickness Required to Mask Against Boron Diffusion.

The mask is thinner for B than for P at the same conditions

Diffusion in solar cell



Diffusion profiles in bipolar transistor



Along red line

resulting profile

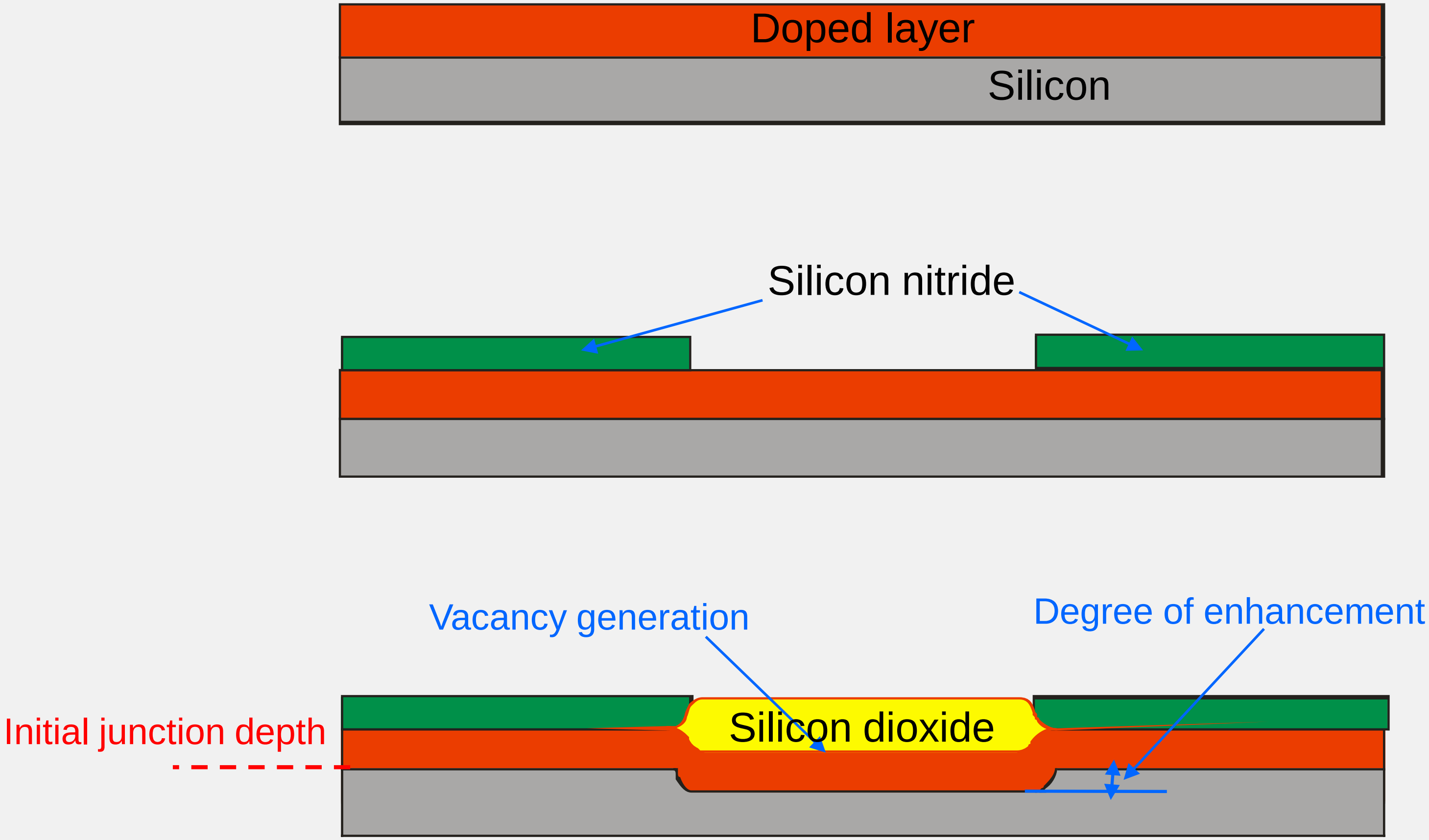
emitter

base

collector

OED in LOCOS

OED –oxidation enhanced diffusion



Doped layer

Silicon

Silicon nitride

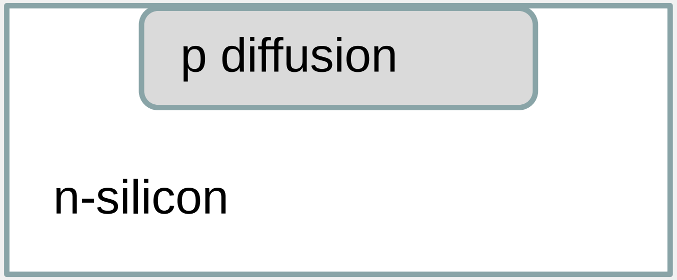
Vacancy generation

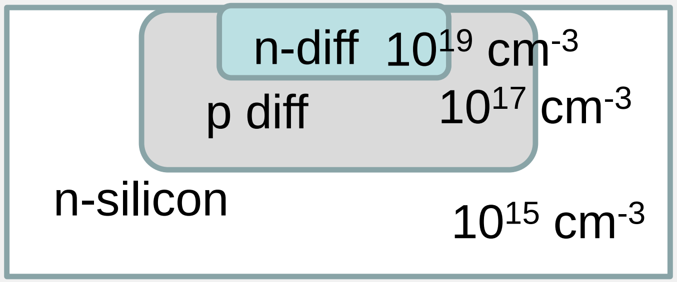
Degree of enhancement

Initial junction depth

Silicon dioxide

Multiple diffusions





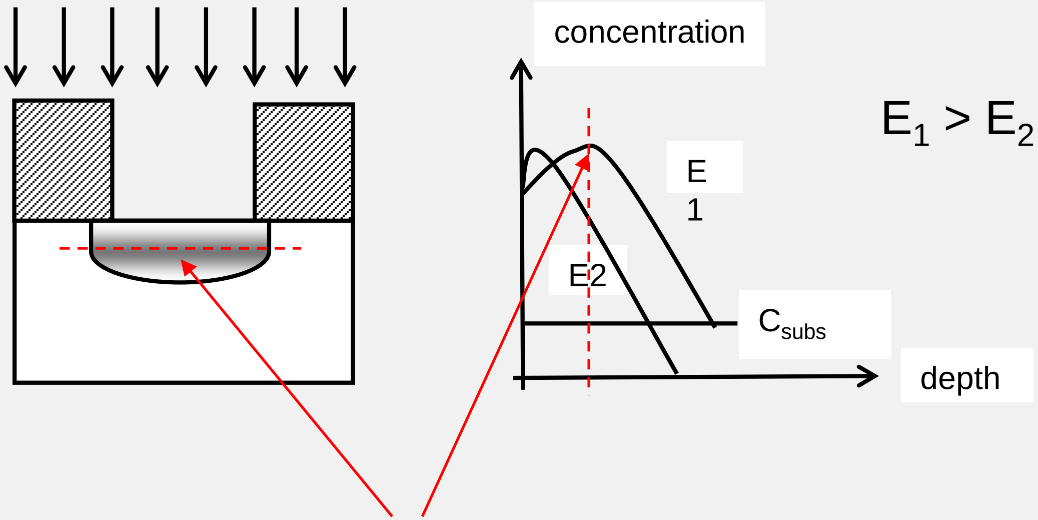
1. Take n-type silicon wafer
2. Thermal oxidation
3. Lithography
4. Oxide mask etching +strip
5. Perform p-diffusion
6. Etch oxide away
7. Thermal oxidation
8. Lithography
9. Oxide etching + strip
10. n-diffusion

    p-diffusion becomes deeper

n-concentration must be higher than p; otherwise dopant type does not change.

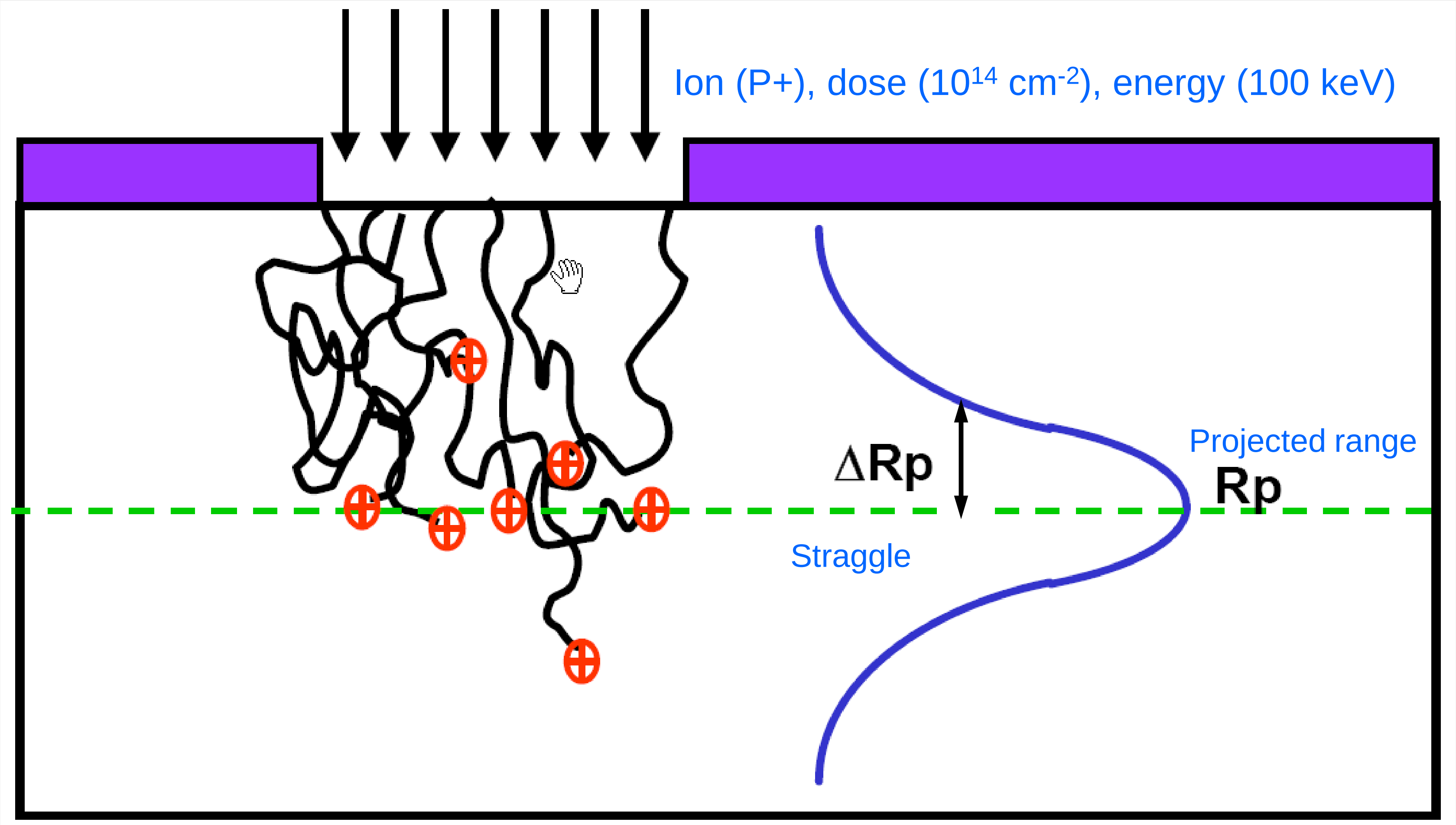
Selective implantation and dopant profile

Room temperature



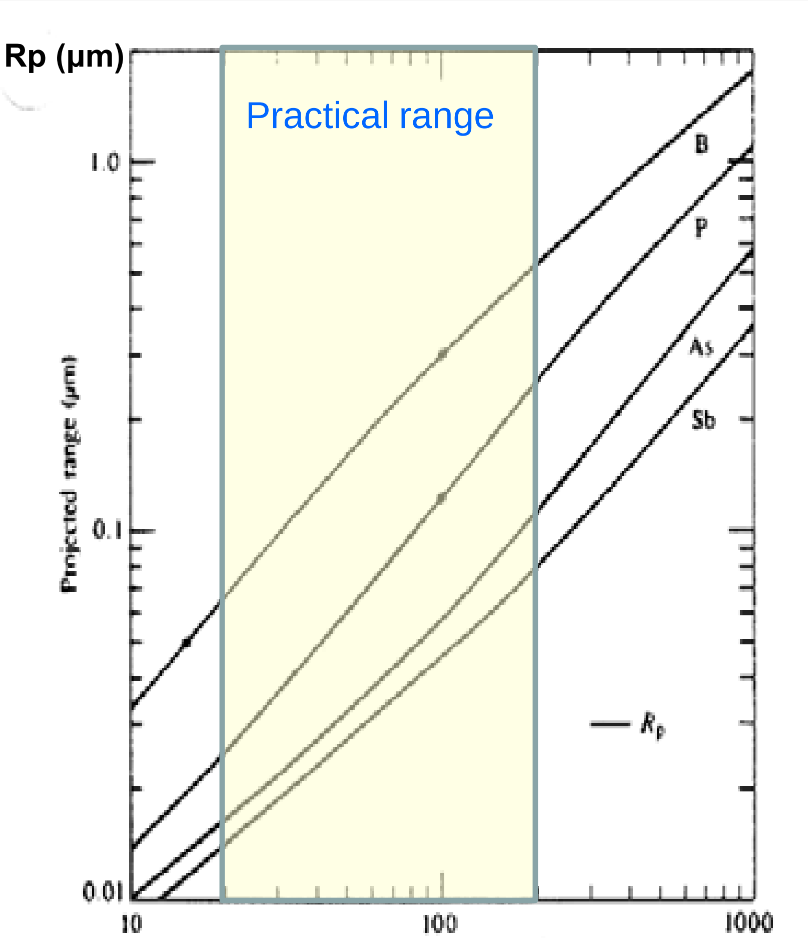
Maximum concentration is below the surface
Compare with diffusion

Projected range and straggle



Ion (P+), dose (10^{14} cm^{-2}), energy (100 keV)

Projected range (R_p) in Si



Ion energy (keV)

***R_p* depends on incident and target atomic masses**

Implantation damage

Can be removed by 1000C at 30s

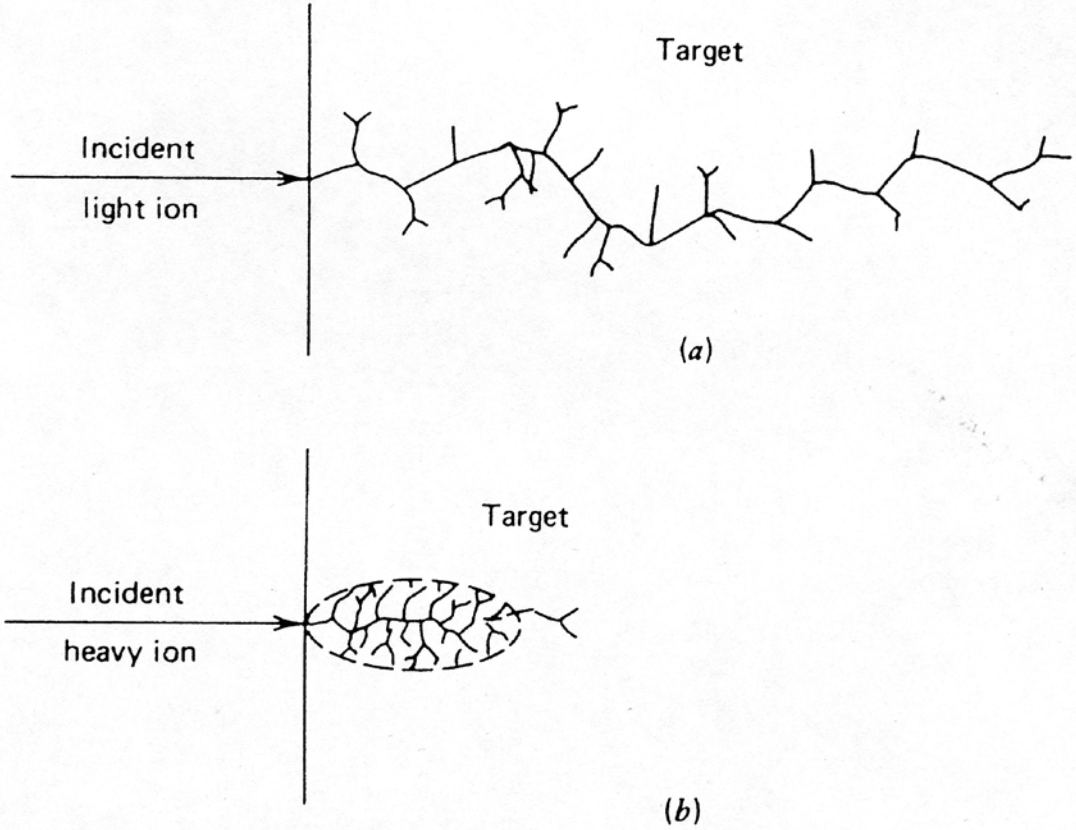
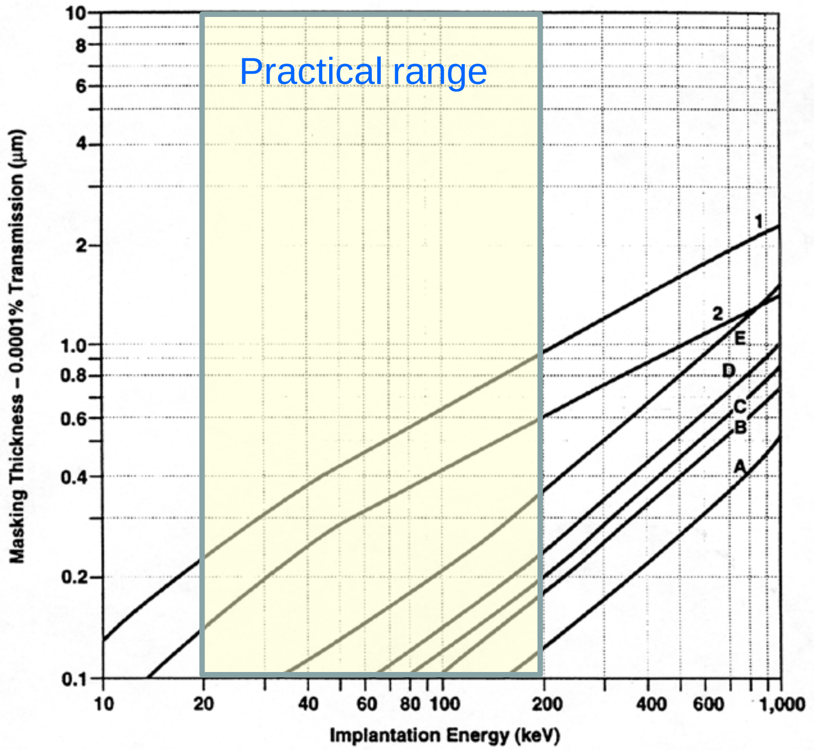


Fig. 6.18 Damage due to (*a*) light ions and (*b*) heavy ions.

Mask thickness for implantation

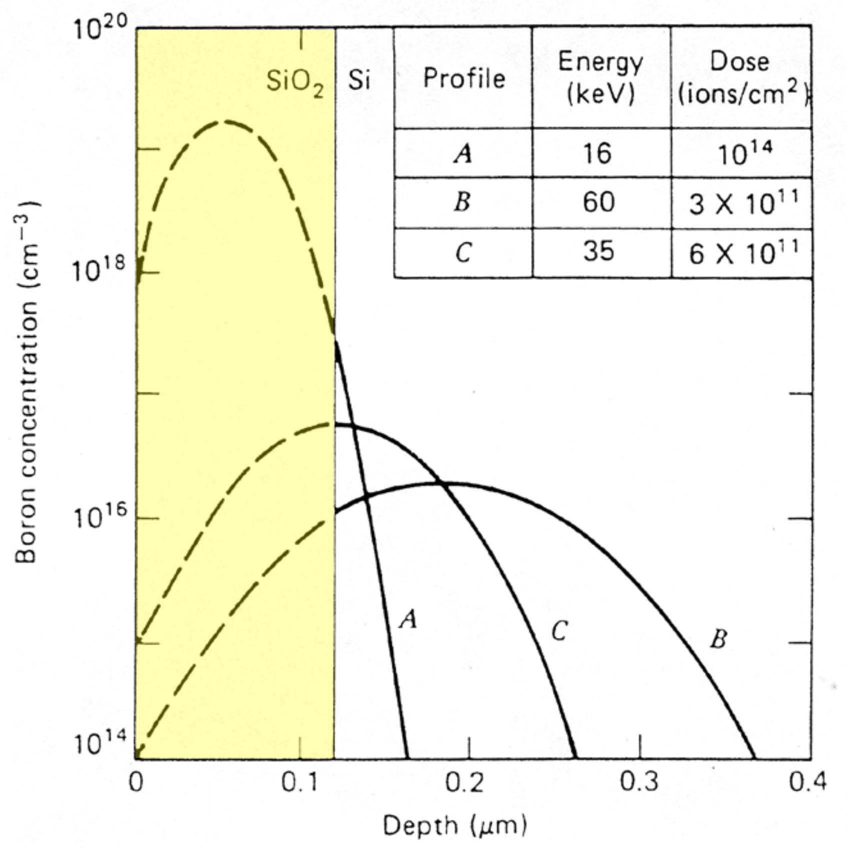


Ion	Curve	Masking Material	Ion	Curve	Masking Material
Boron (Top)	1	Thermal SiO_2, Polysilicon, Aluminum, Negative Resist, or Positive Resist.	Antimony (Bottom)	A	CVD Si_3N_4
				B	Thermal SiO_2 or Aluminum
				C	Polysilicon
	2	CVD Si_3N_4		D	Negative Resist
				E	Positive Resist

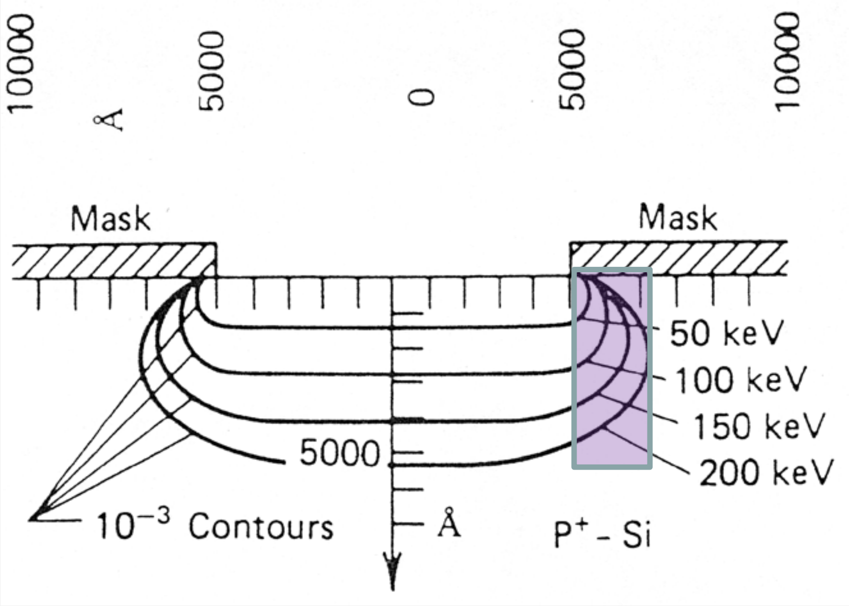
Source: Technology Associates 14666

Figure 4-61. Masking Thickness Required, Boron and Antimony Implants.

Simulated implantation profiles



Profile	Energy (keV)	Dose (ions/cm^2)
A	16	10^{14}
B	60	3×10^{11}
C	35	6×10^{11}



Measured implantation profiles

Boron

Phosphorus

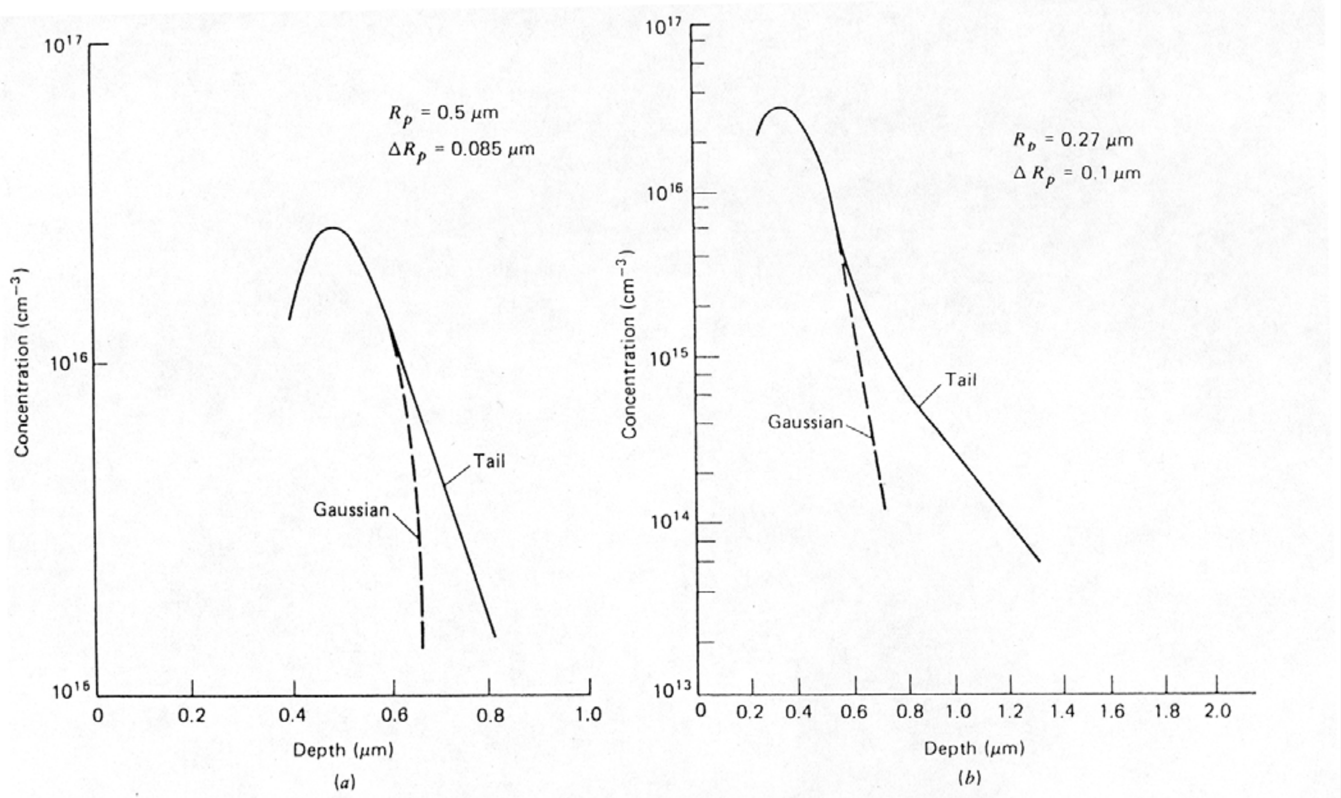


Fig. 6.3 Ion concentration. (*a*) Boron in silicon, 250-keV ions, annealed at 850°C for 30 min. Adapted from Moline [5]. (*b*) Phosphorus in silicon, 300-keV ions, annealed at 800°C for 30 min. Adapted from Dearnaley et al. [3].

Implant parameters

Ion energies 10-200 keV

Implant depths 10-500 nm

Doses 10^{11} to 10^{16} ions/cm^{-2}.

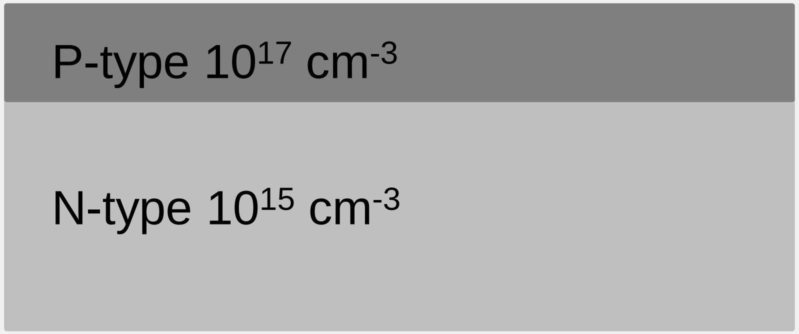
Concentrations ca. 10^{15} cm^{-3} to 10^{20} cm^{-3}.

$5 \cdot 10^{15}$ cm^{-2} ion implant dose and depth of ca. 200 nm translates to ca. 25 Ohm/sq sheet resistance

Doping level

Wafers always come doped: 10^{13}-10^{20} cm^{-3} of dopant.

Diffusion and implantation can **add** dopants ➔ doped region dopant concentration always higher than original wafer.



P-type 10^{17} cm^{-3}

N-type 10^{15} cm^{-3}

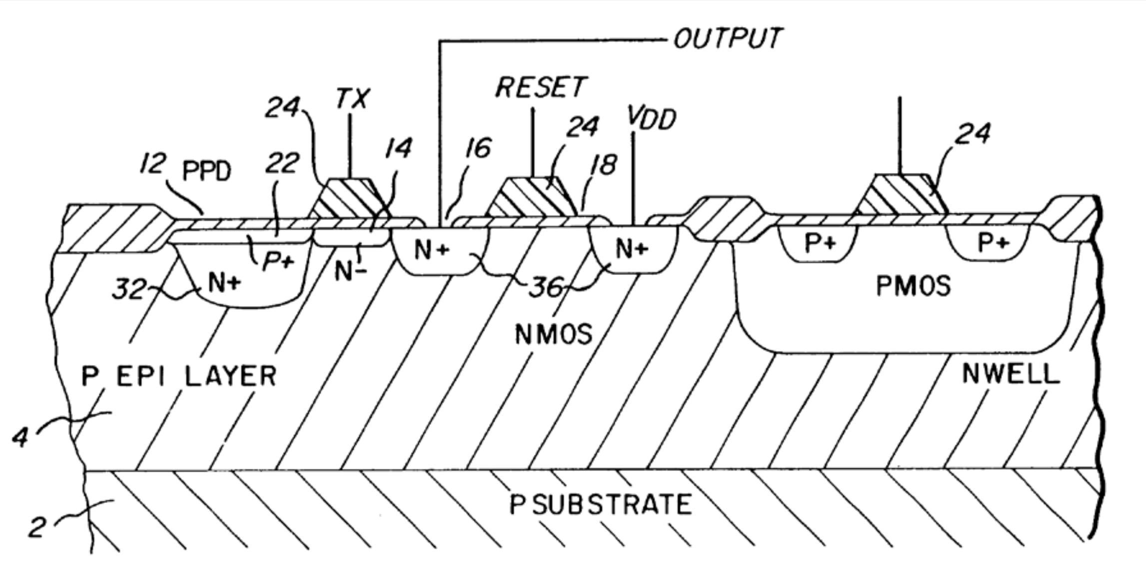
Possible

P-type 10^{15} cm^{-3}

N-type 10^{17} cm^{-3}

Impossible by diffusion/implantation

In which order are dopings made ?



US 6297070 B1

p-epi layer growth
Deepest first (NWELL)

Shallowest last (p+)

It is possible to do litho-implant-litho-implant, and one annealing step to cure the damage and drive the dopants deeper, e.g. medium depth n+ and p+ in the figure could be combined this way.

Implantation advantages

Implantation is:

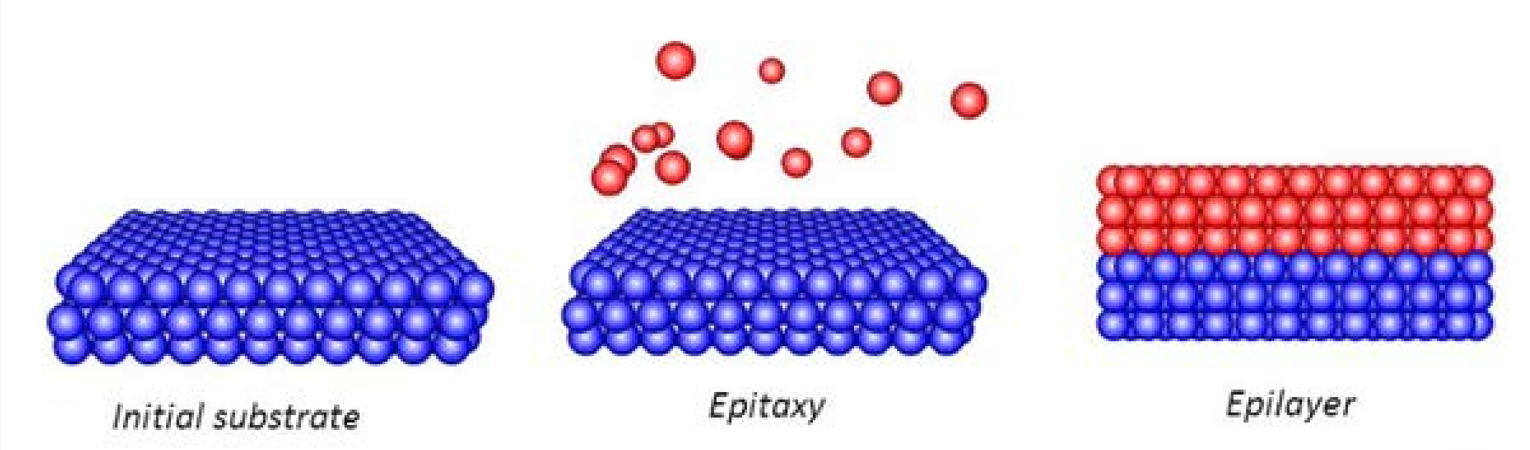
- more accurate and uniform in dose control
- produces greater variety of profiles
- possible through oxide and nitride
- provides wide selection of mask materials
- less sensitive to surface cleaning procedures

Implantation vs. diffusion

- Sideways spreading in diffusion ≈ depth
- Sideways spreading in implantation is ≈ 1/3 depth
- Diffusion is high-temperature process ➔ needs oxide or nitride mask
- Implantation is room temperature process ➔ resist mask

  but: damages after implantation are annealed at high temperature ➔ both need ca. 1000^{o}C
- Diffusion is the best for high doping level, deep junctions and double side doping

Epitaxy - "arranging upon"



Common epitaxy pairs (heteroepitaxy):

Epitaxy conditions:

Substrate and film are single crystalline

Crystal lattices are closely matching

Si wafer – CaF_2, Y_2O_3, $CoSi_2$, CeO_2

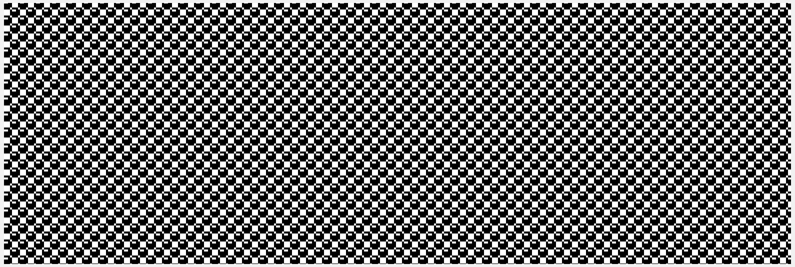
Sapphire wafer - Si, GaN

CeO_2 film – YBCO (yttrium barium copper oxide)

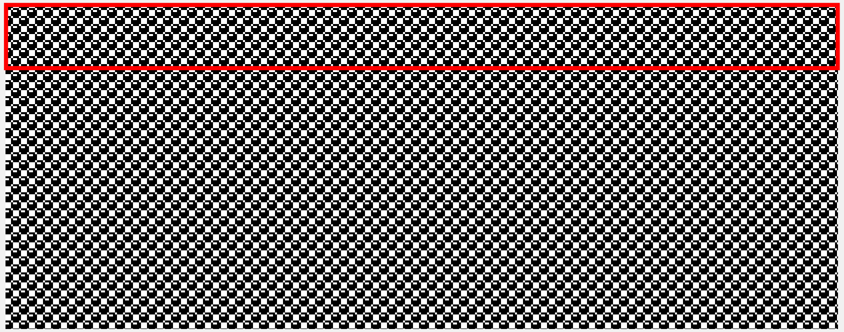
GaAs wafer – GaAlAs/GaAs

Homoepitaxy

Crystalline film A on top a crystalline wafer A



Single crystal wafer

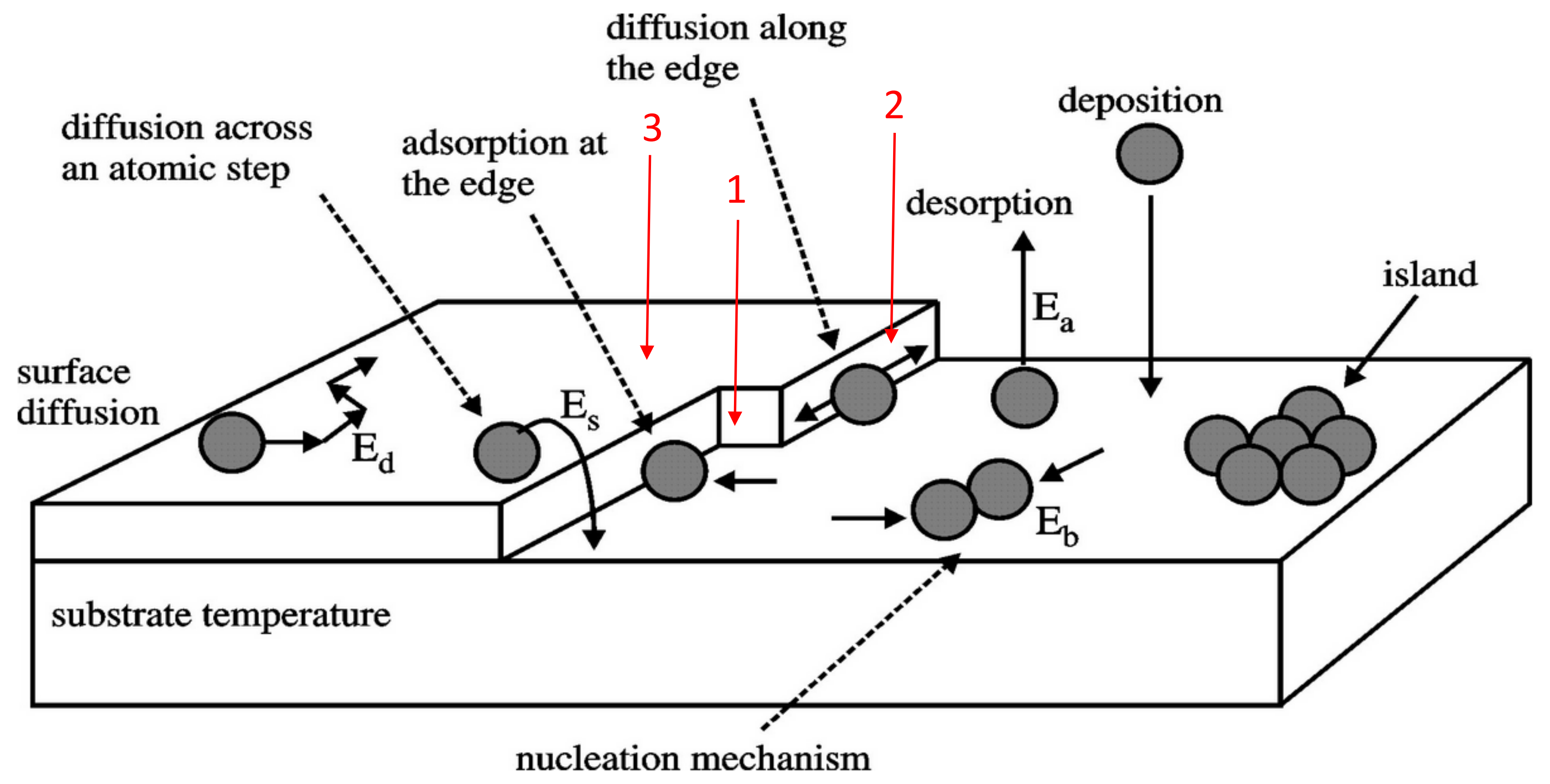


Epitaxial layer of the same material deposited on top

Why epitaxy of *c*-Si on *c*-Si (homoepitaxy)?

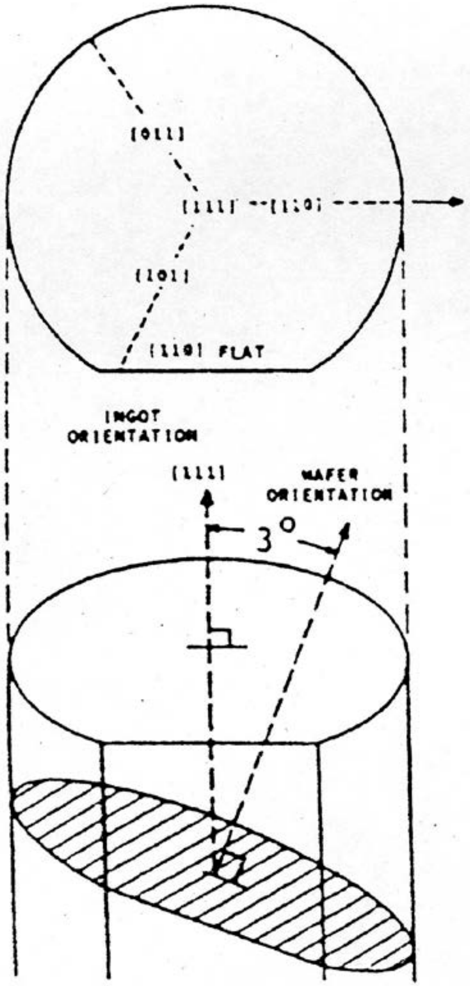
1. Freedom in the order of doping
2. Absence of O_2 and C contaminations

Preferable nucleation places: kink growth model



https://www.physik.uni-kl.de/hillebrands/research/methods/molecular-beam-epitaxy/

Miscutting of (111) wafers

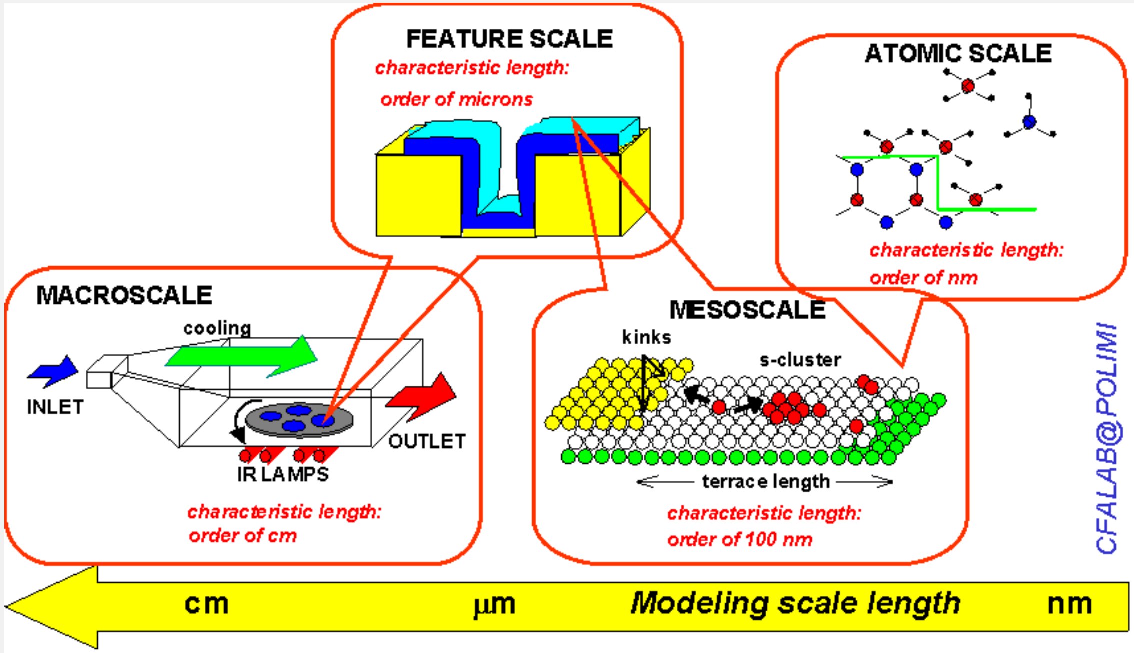


Wafer Orientation

(111) Off 3°
Toward (110)

(111) WAFER-CUT OFF-ORIENTATION.

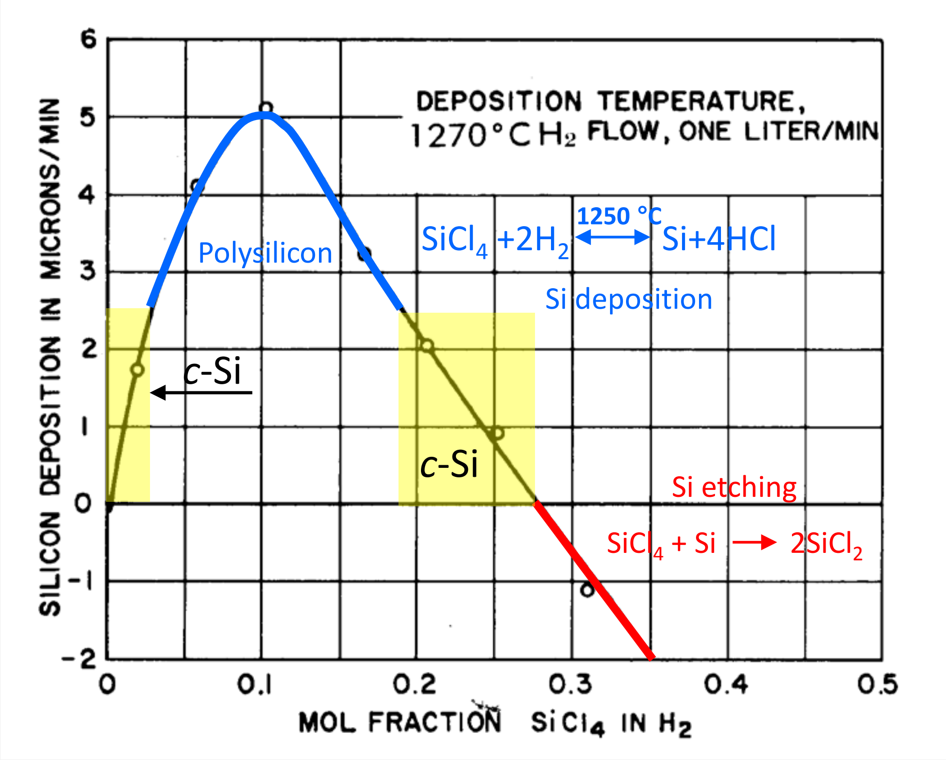
Vapor-Phase Epitaxy (VPE)



VPE is modified CVD

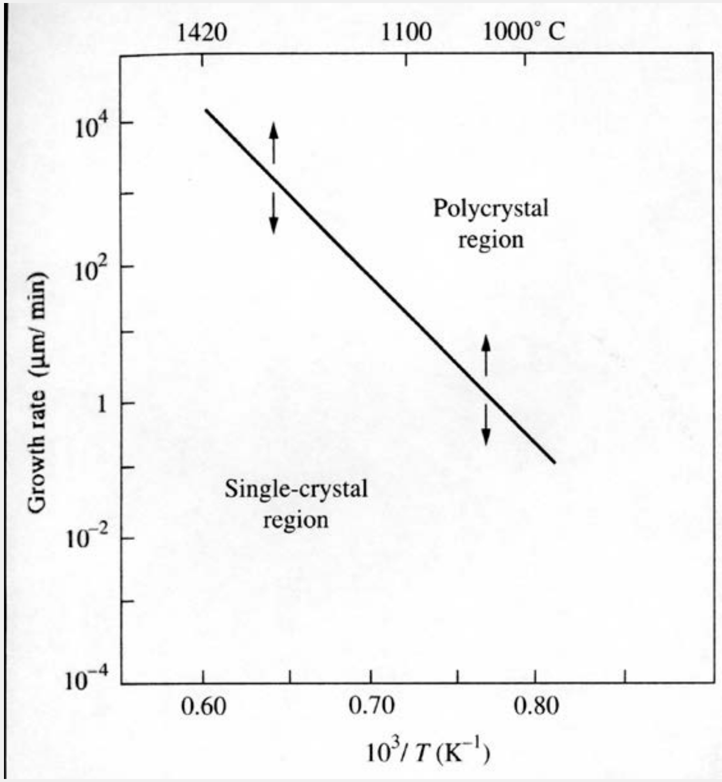
http://www.mat.unimi.it/users/mirwork/Crystals/abstracts.html

Si epitaxy conditions

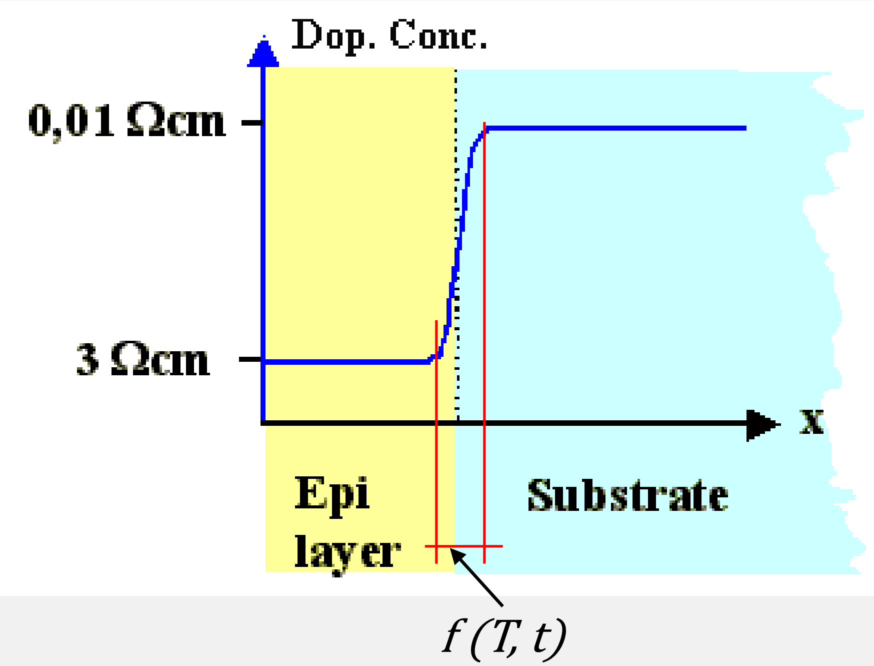


$SiCl_4 + 2H_2 \xleftrightarrow{1250\ °C} Si + 4HCl$

$SiCl_4 + Si \longrightarrow 2SiCl_2$



Dopant diffusion during epi



Because epitaxy is a high temperature process, dopant atoms diffuse during epitaxy.

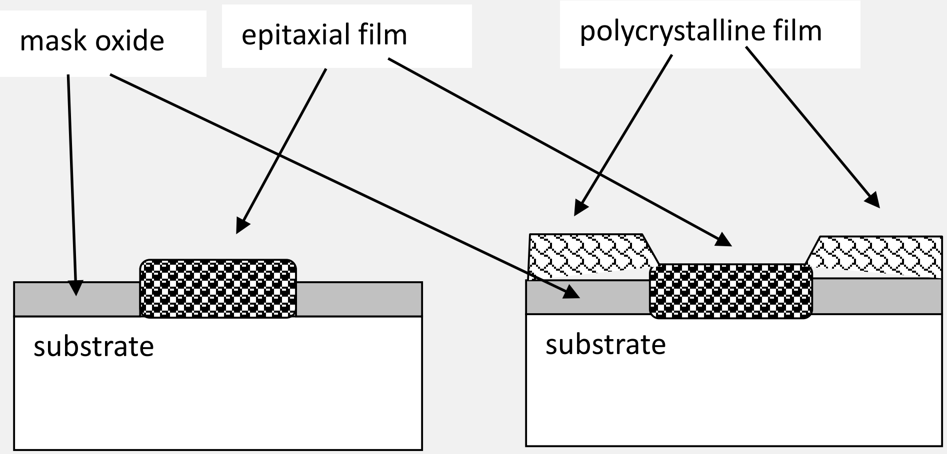
Diffusion is from high dopant concentration to low concentration.

Epi doping level is independent of substrate doping level, but the interface is not sharp due to diffusion.

Lightly doped epi

Heavily doped substrate

Selective epitaxy



mask oxide

epitaxial film

polycrystalline film

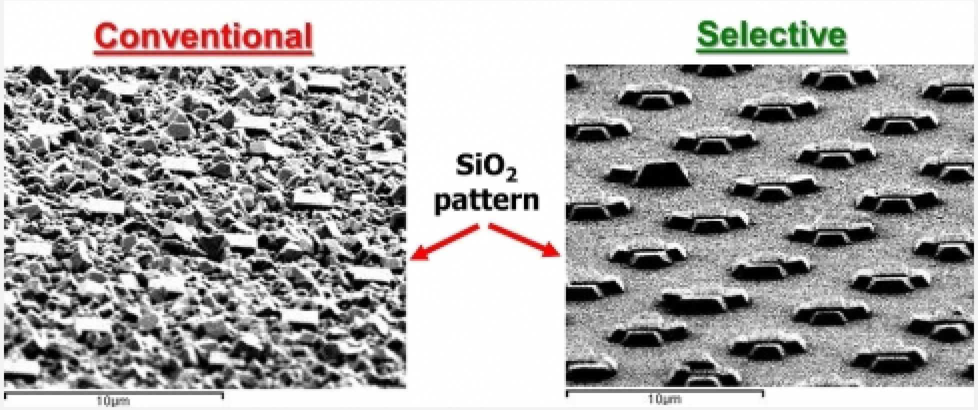
substrate

substrate

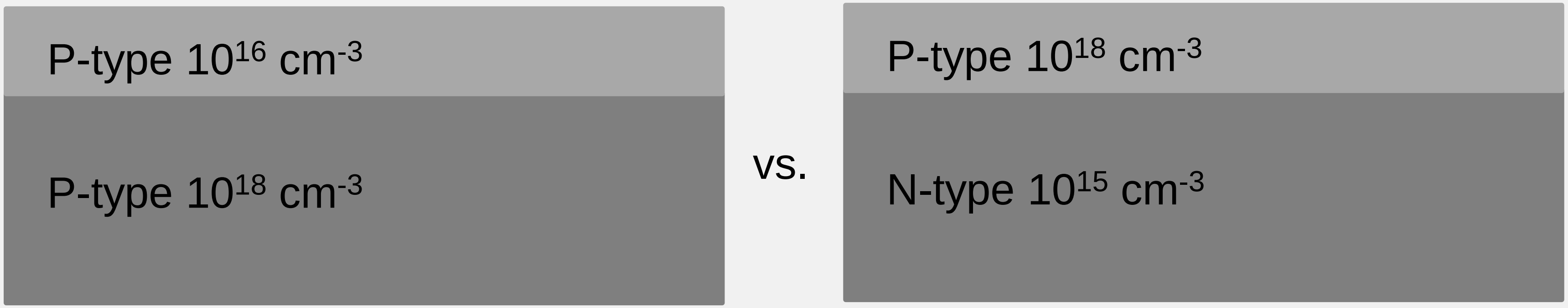
No deposition on oxide

Blanket deposition

GaN on c-Si (100)



Doping with epitaxial layers



P-type 10^{16} cm^{-3}

P-type 10^{18} cm^{-3}

vs.

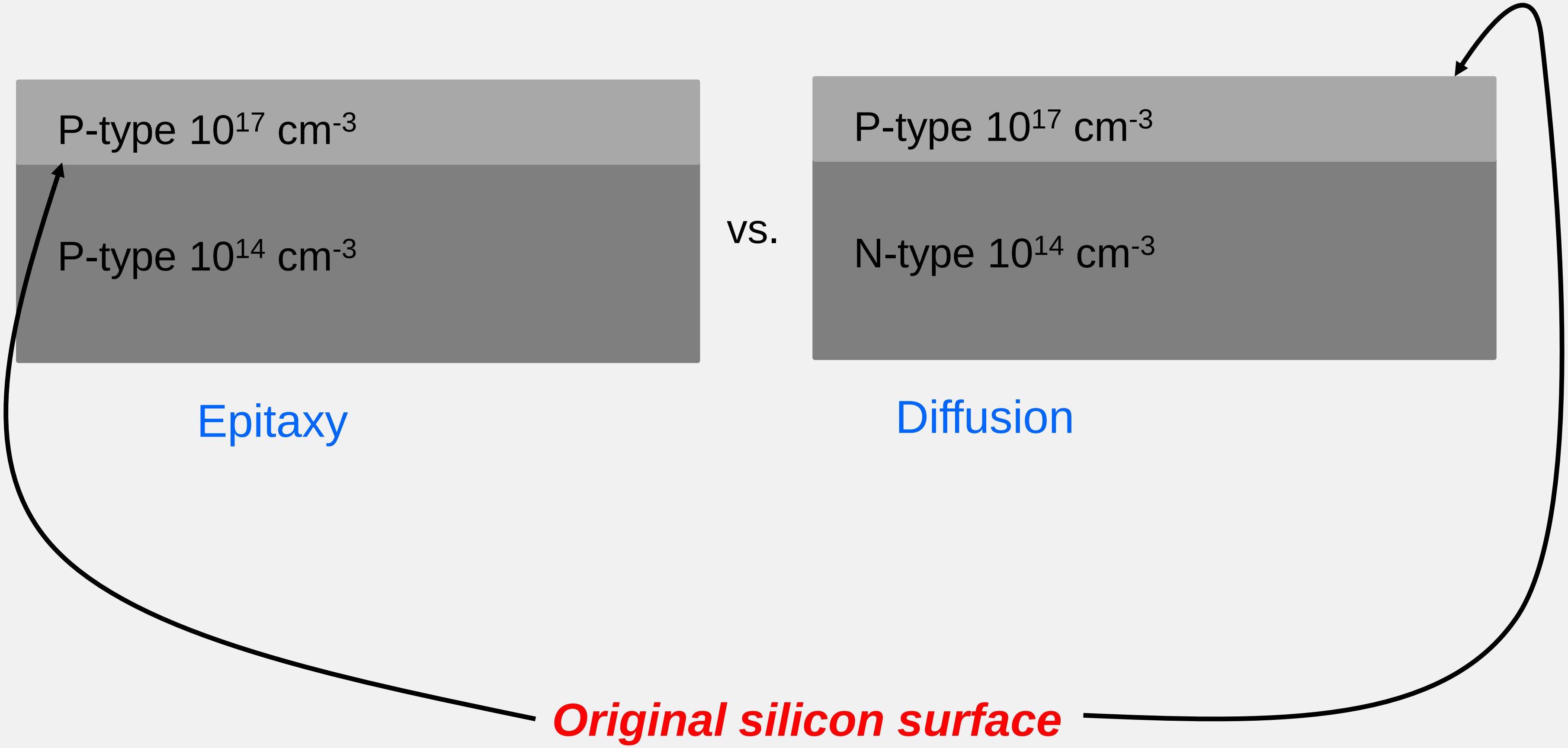
P-type 10^{18} cm^{-3}

N-type 10^{15} cm^{-3}

Epitaxy is the only way to get this.

Thick doped layer or uniform dopant profile.

Epitaxial layer vs. diffused layer



P-type 10^{17} cm^{-3}

P-type 10^{14} cm^{-3}

vs.

P-type 10^{17} cm^{-3}

N-type 10^{14} cm^{-3}

Epitaxy

Diffusion

Original silicon surface

Summary

- Epitaxy is suitable for uniform doping of monocrystalline Si layers from 100 nm to 100 µm
- Purity of epilayers is higher than Si substrate one
- Epitaxy is limited by monocrystalline substrate with matching lattice cells