Doping. Epitaxy

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Chapters 6, 14, 15

Previous lectures

- Oxidation
- Lab device

Next lecture

- Bonding and CMP

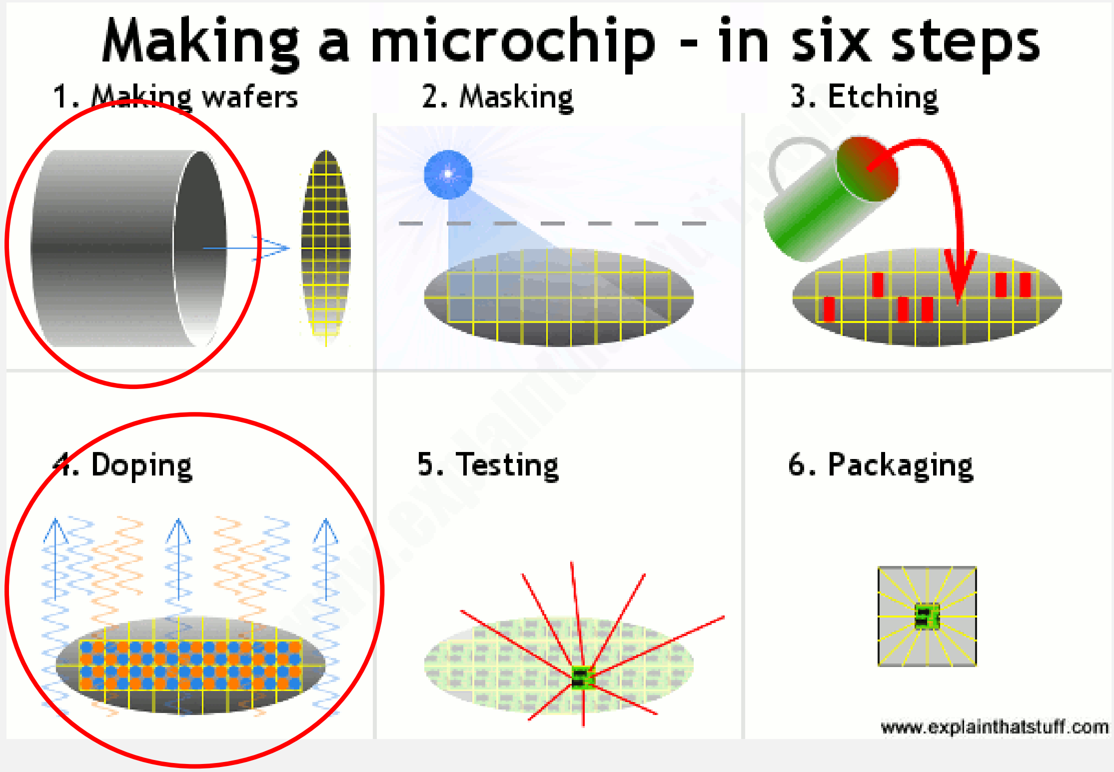
Outline I

- Selective doping
  - Diffusion
  - Implantation
- Epitaxy

Outline II

Ingot doping

Wafer doping, selective or blank

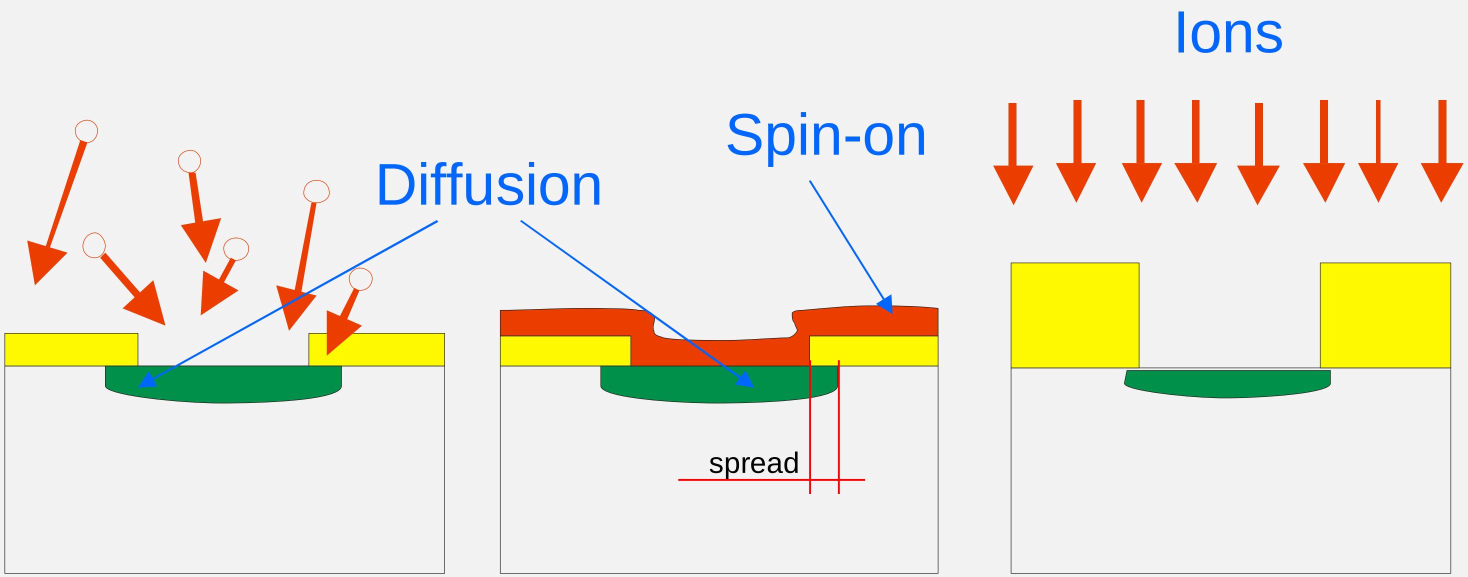


Types of doping

- Blank doping (wafer, ingot)
  - during crystal growth (doped raw Si)
  - during epitaxy (gas containing dopant)

- Selective doping
  - by ion implantation (ions of dopant)
  - by diffusion (gas or solid dopant)

Selective doping by phosphorus



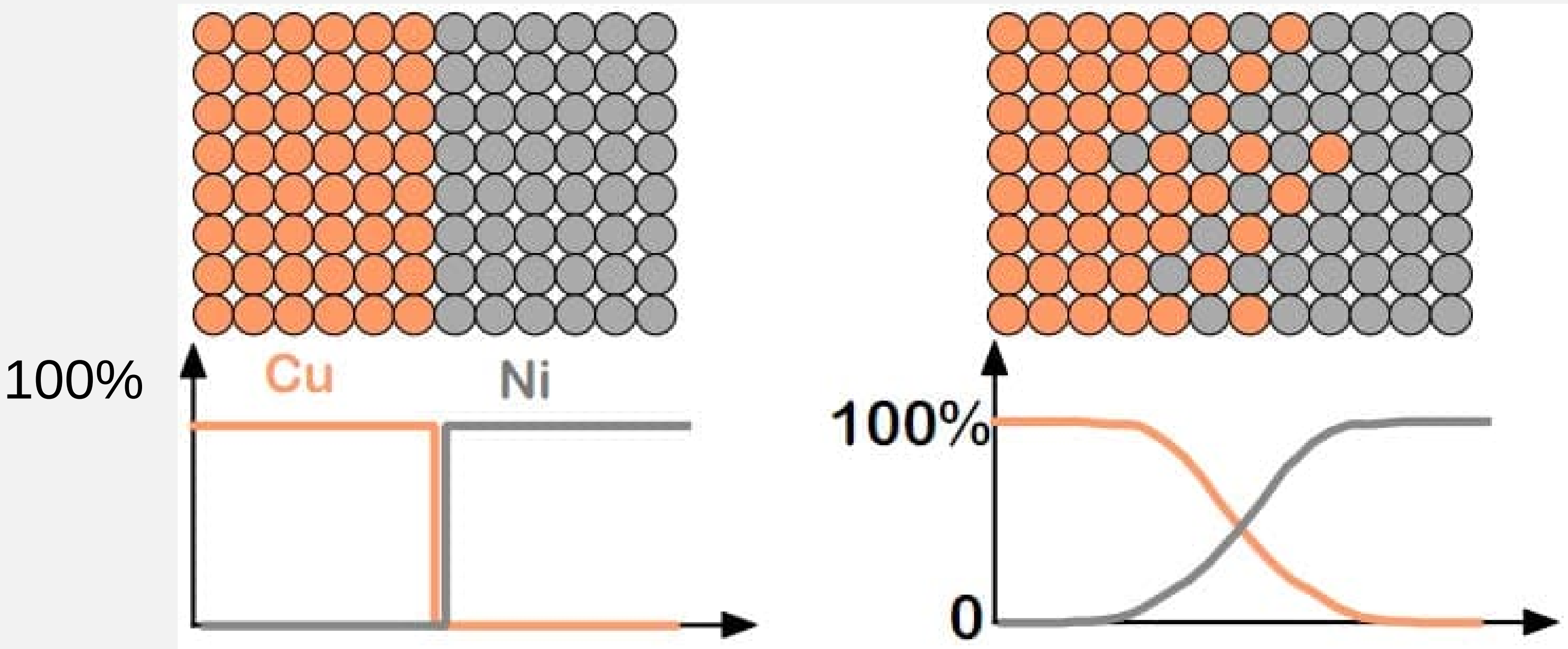
Gas phase doping	Solid-source doping	Ion implantation
Oxide as a mask	Oxide as a mask	Photoresist as a mask
$POCl_3$ as a source	P_2O_5 as a source	Accelerated P^+ as a source
1000ºC	1000ºC	Room temperature?
Lateral spread = depth	Lateral spread = depth	Lateral spread = 1/3 depth

Diffusion

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

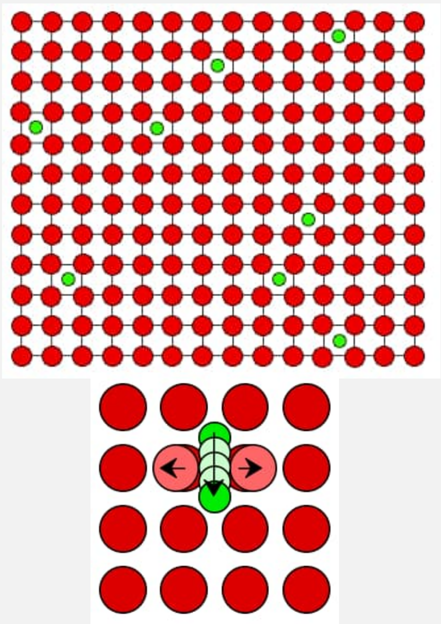


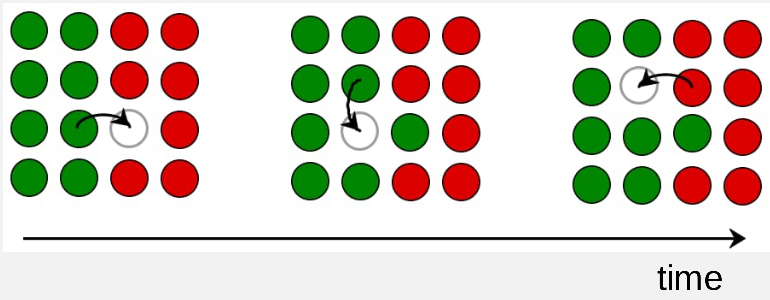
Concentration profile

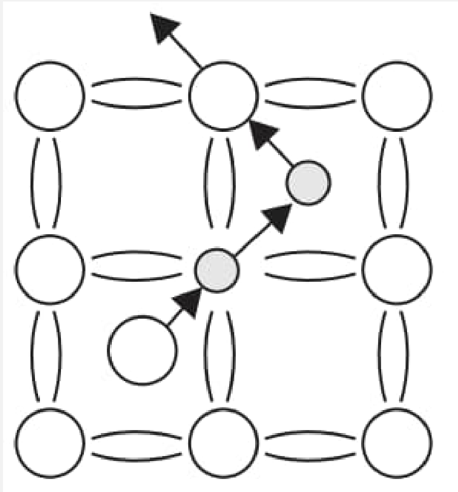
Concentration profile

Diffusion mechanisms in perfect lattice

Interstitial	Substitutional As, Sb	Interstitialcy B, P







E_a = 1-1.5 eV	E_a = 3.5-4 eV	E_a = 3.5-4 eV

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

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

- 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

For boron in Si at 950 ^{o}C

D = 4.3 × 10^{-15} cm^2/s

At 1050 ^{o}C

	Boron	**Phosphorous**
D_o (cm^2/s)	0.76	3.85
E_a (eV)	3.46	3.66
D (cm^2/s)	5.2 × 10^{-14}	4.5 × 10^{-14}
x (µm), 1h	0.27	0.25

Characteristic diffusion length

For infinite dopant source distribution depends fully on characteristic length *X* at which impurity concentration is $C \sim C_s/2$, where C_s is surface concentration of dopant

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

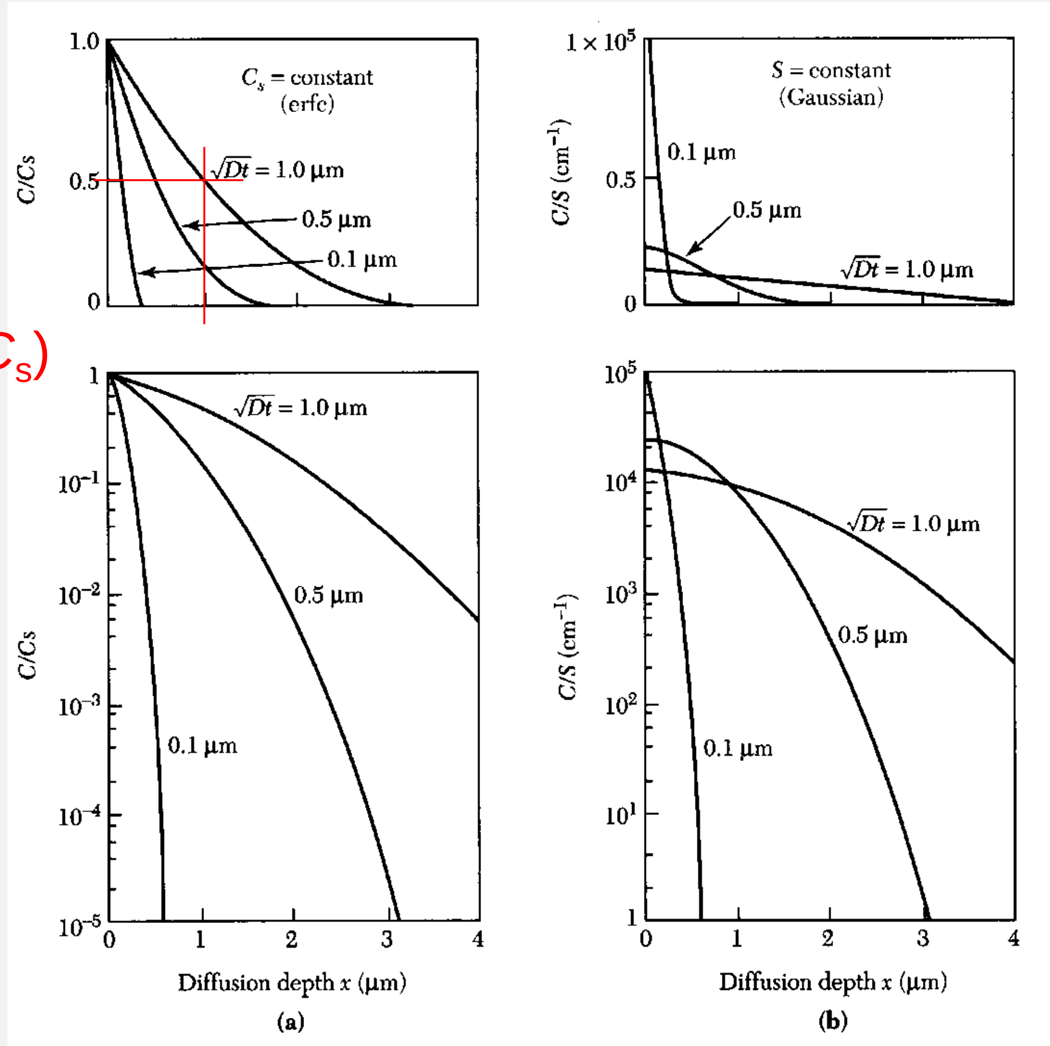
Diffusion profiles: dopant concentration

Infinite source | Limited source or drive-in

Linear

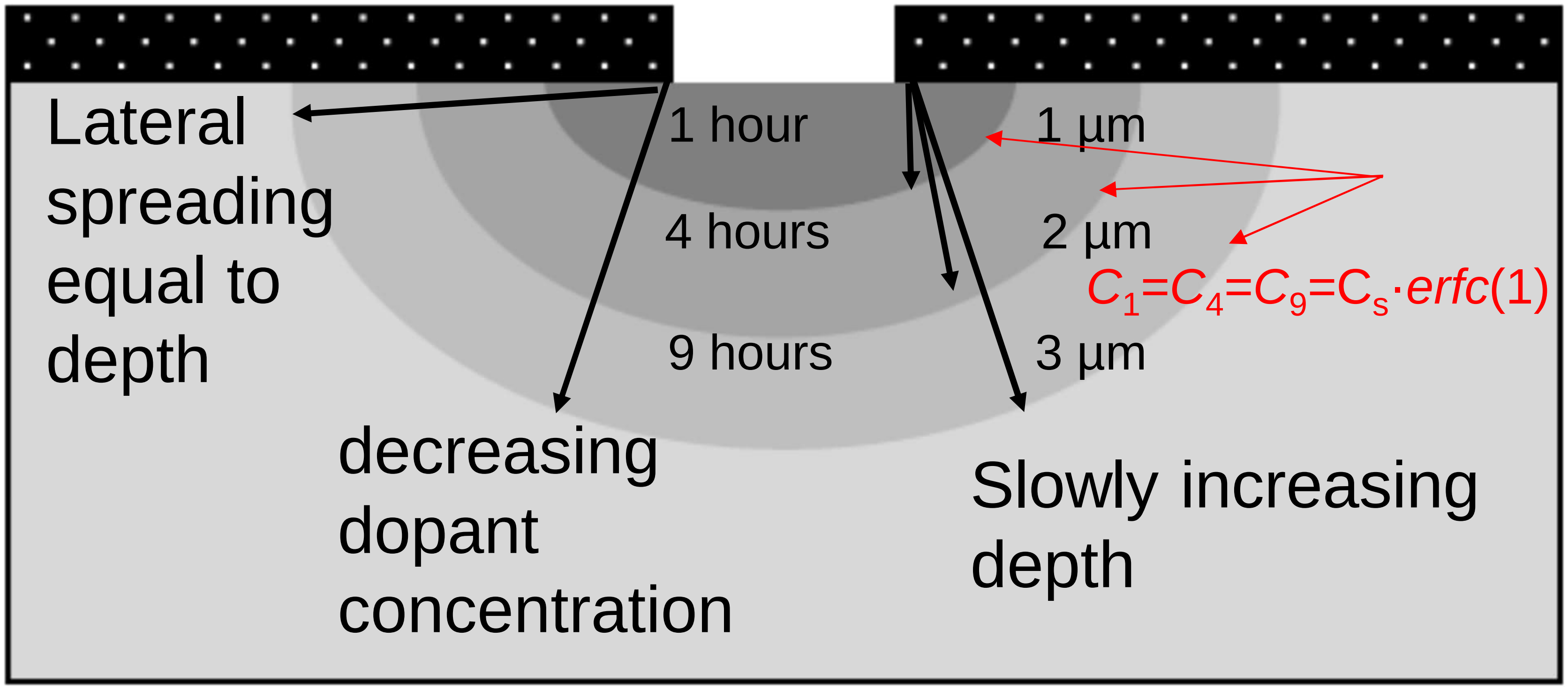
Logarithmic

$x=\sqrt{4Dt} \times erfc^{-1}(C/C_s)$



S – area below a curve

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



Realization and measurement

- Diffusion is done 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
- 4-point probe, SIMS, SRP

Mask thickness for selective diffusion

Usually, dopant transmission through mask is below 0.0001%

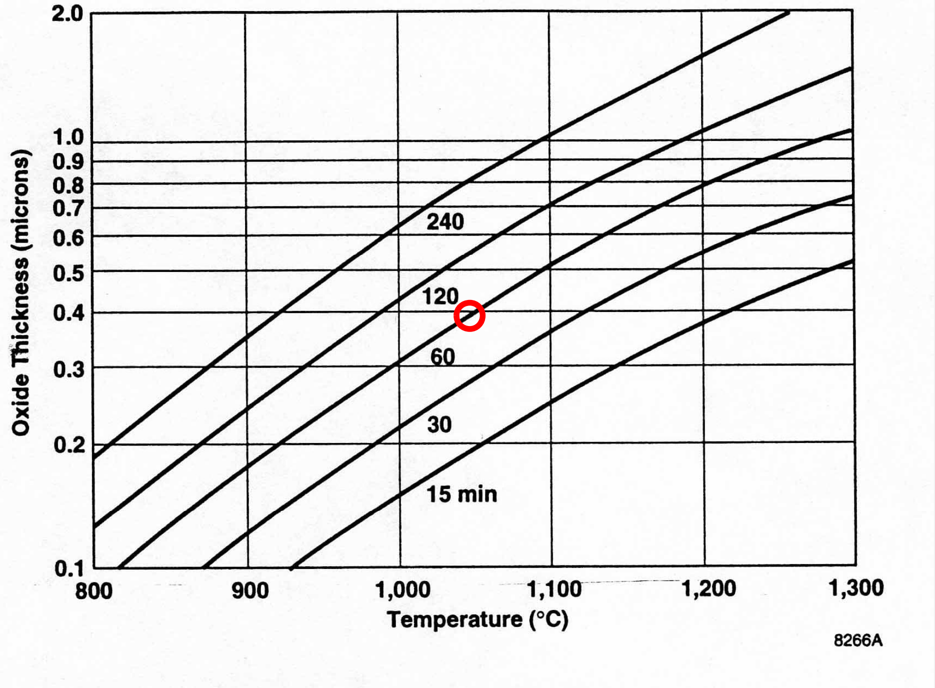


Figure 4-19. Oxide Thickness Required to Mask Against Phosphorus Diffusion.

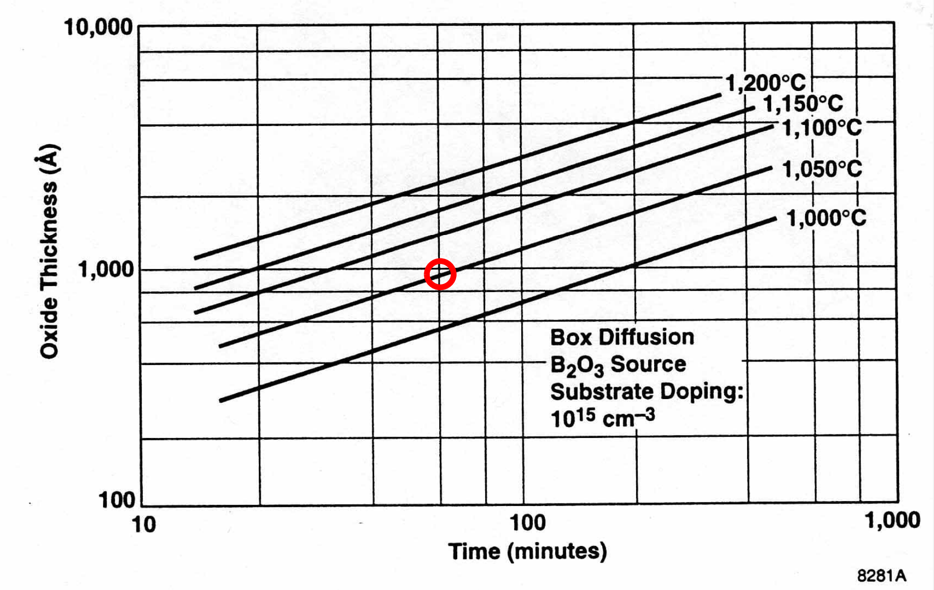
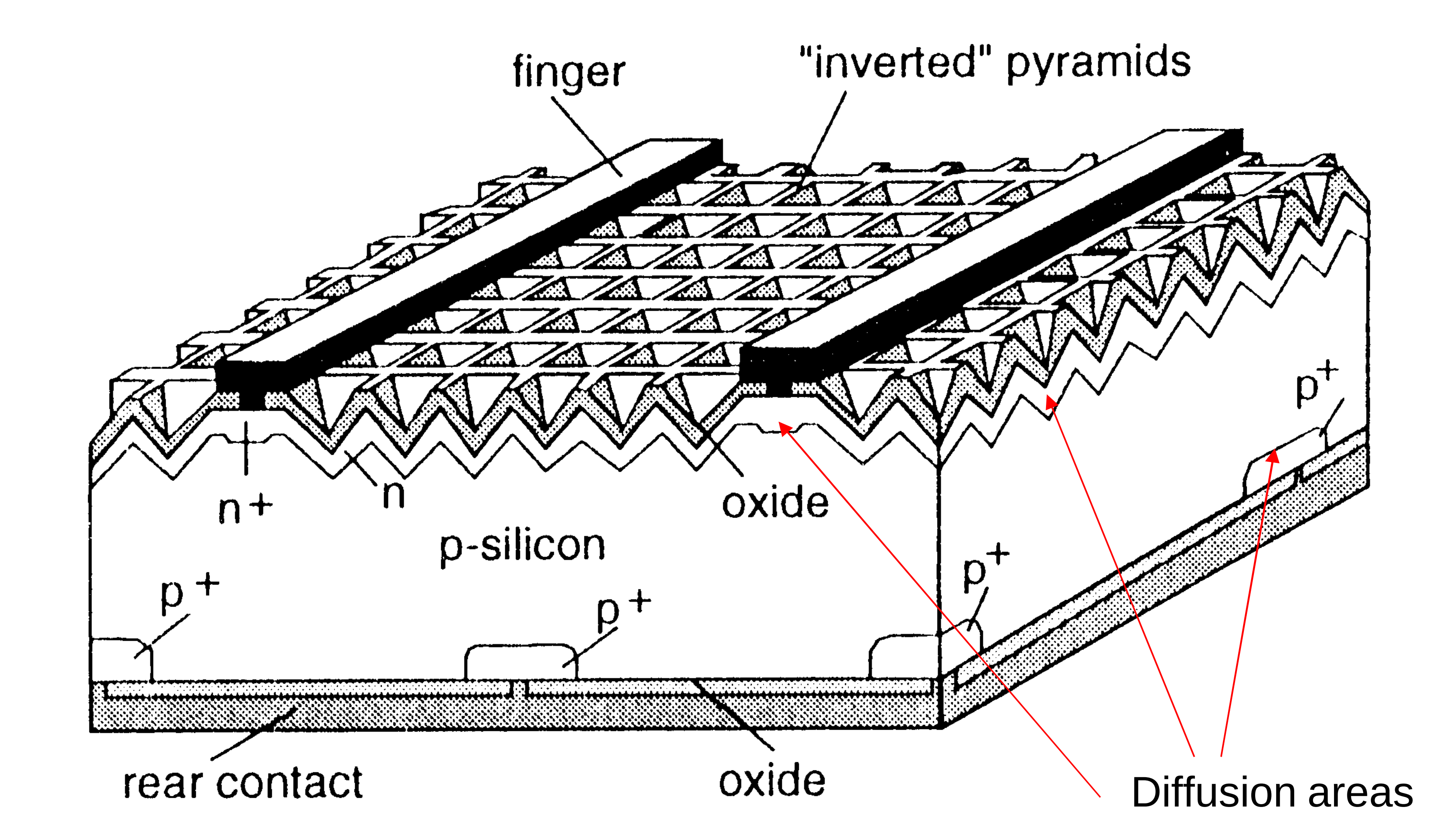


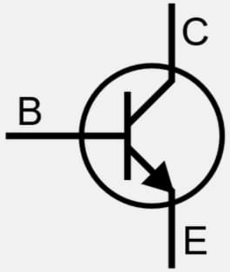
Figure 4-20. Oxide Thickness Required to Mask Against Boron Diffusion.

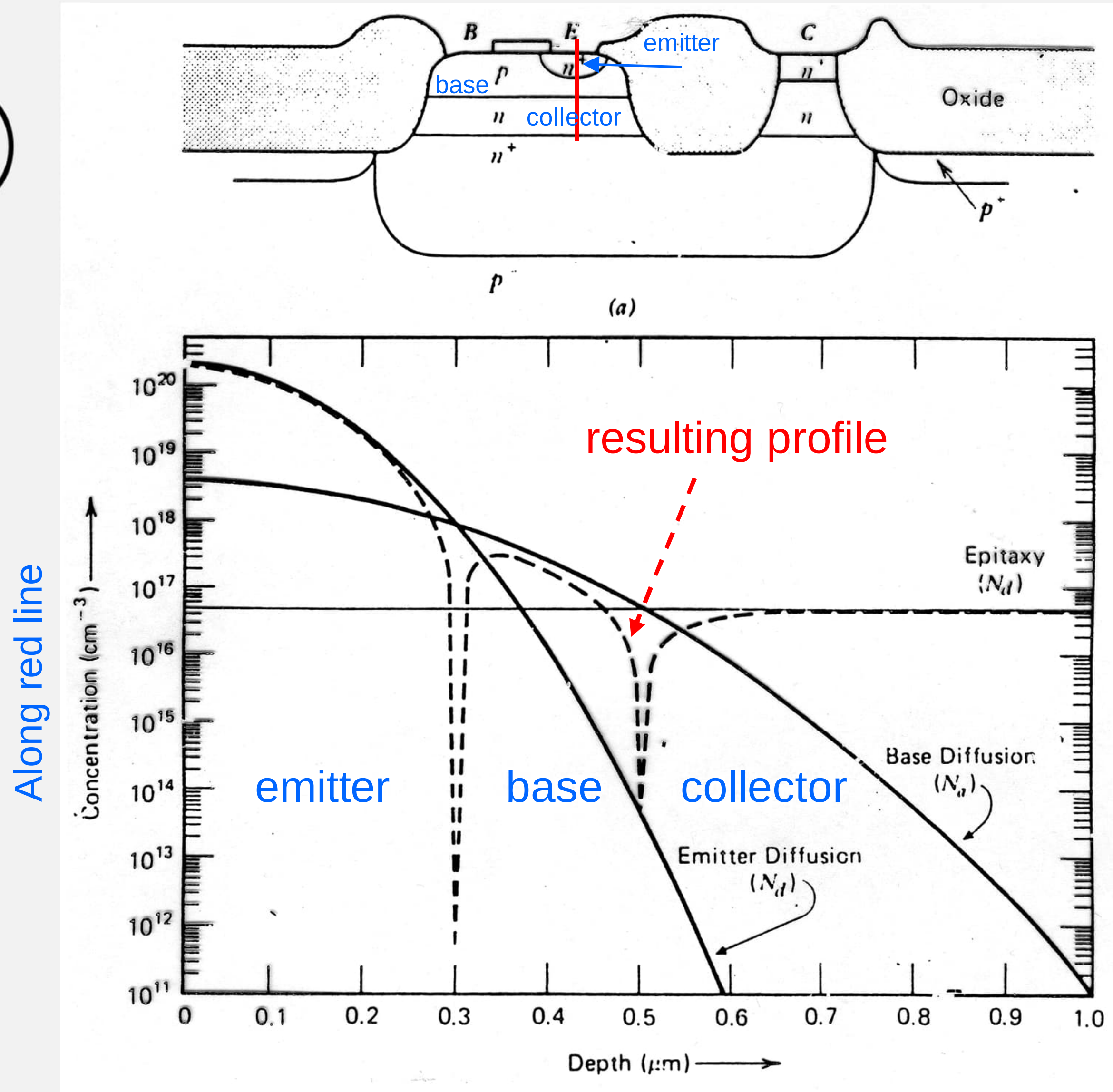
The mask is thinner for B than for P at the same conditions

Diffusion in solar cell



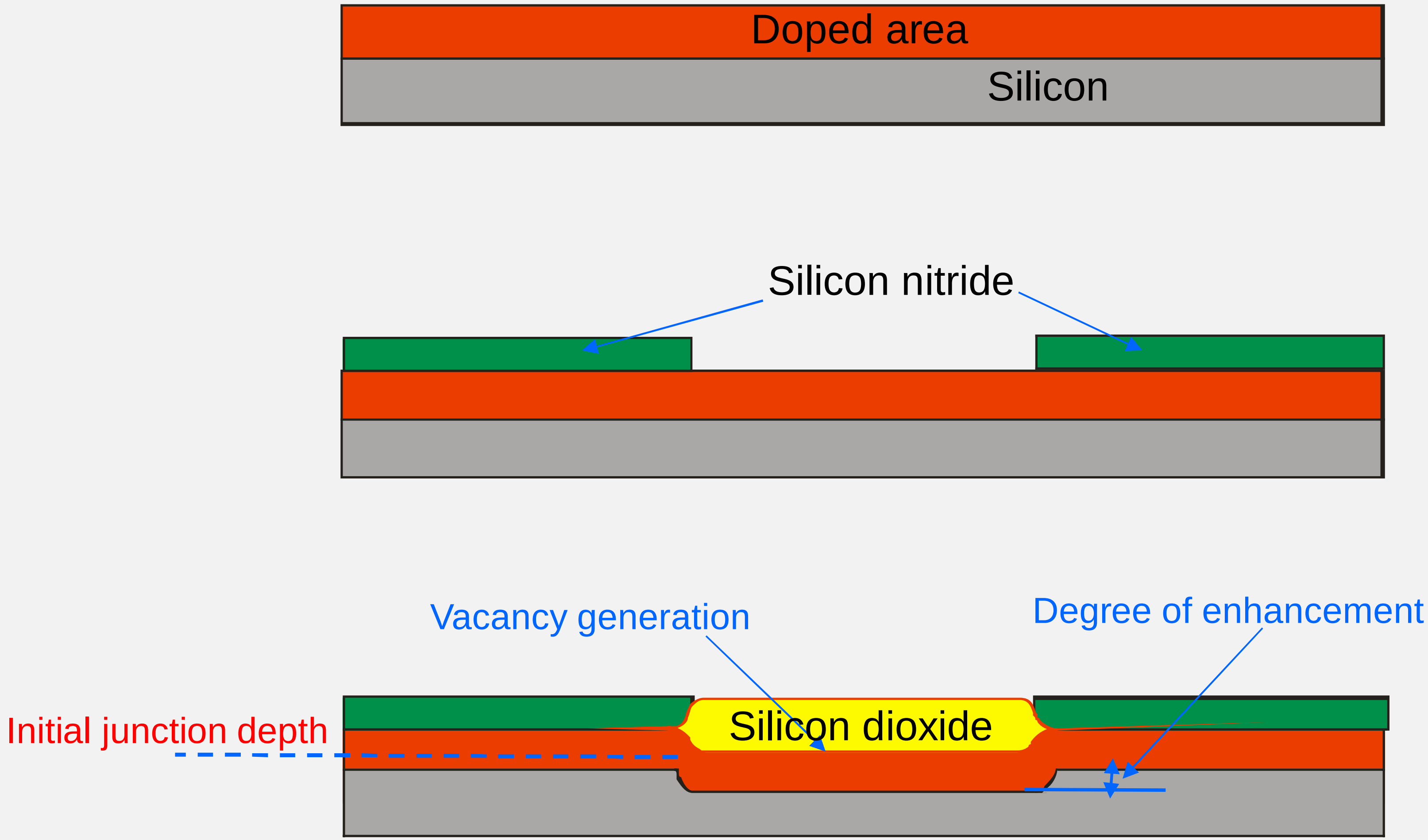
Diffusion profiles in bipolar transistor



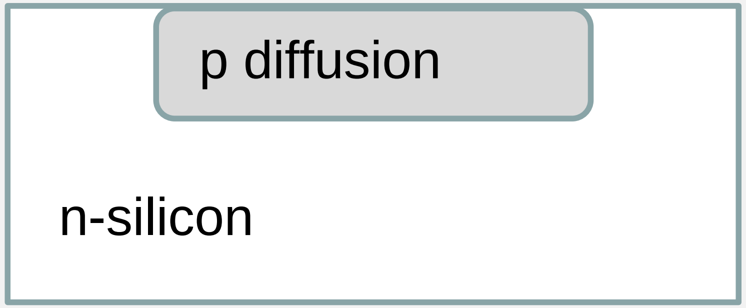


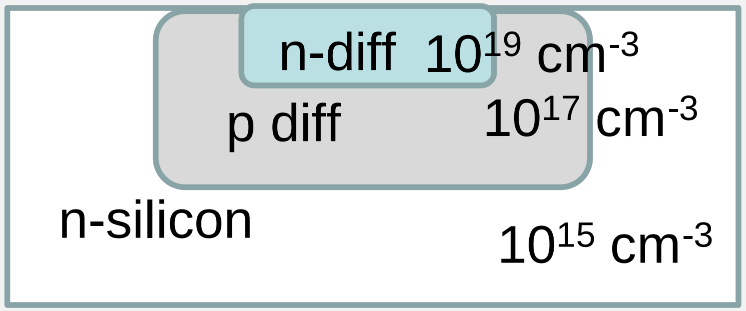
OED in LOCOS

OED –oxidation enhanced diffusion



Multiple diffusions



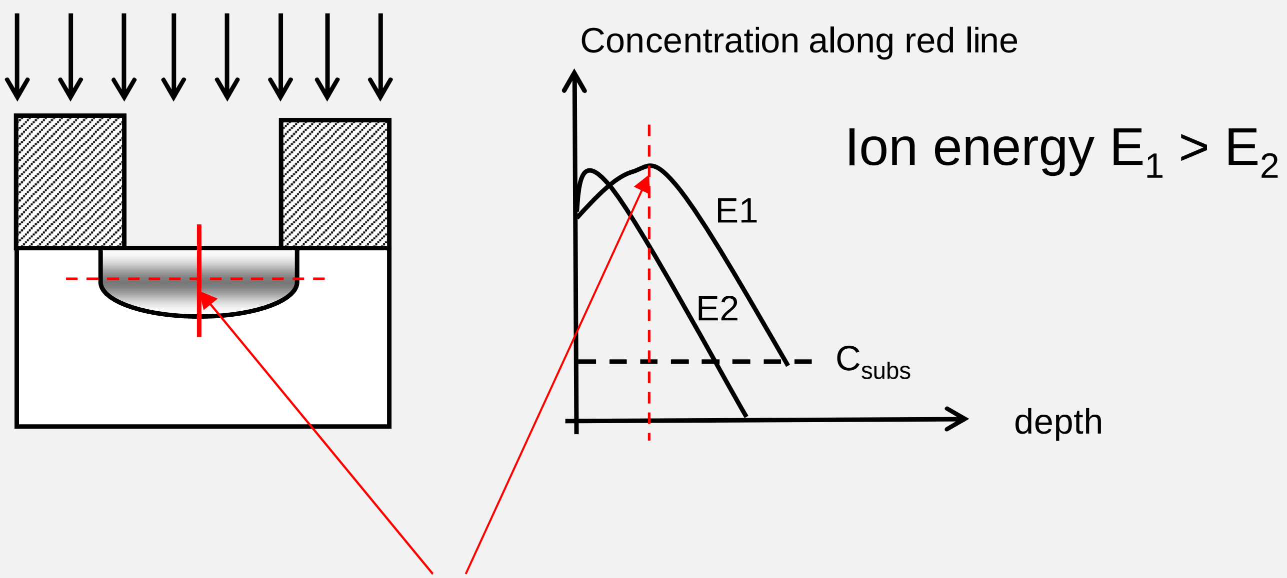


1. Take n-type silicon wafer
2. Thermal oxidation
3. Lithography
4. Oxide mask etching +strip
5. Perform *p*-diffusion
6. Etch oxide away
7. Thermal oxidation
8. Lithography
9. Oxide etching + strip
10. *n*-diffusion;
    p-diffusion becomes deeper

n-concentration (step 10) must be higher than *p*; otherwise dopant type does not change.

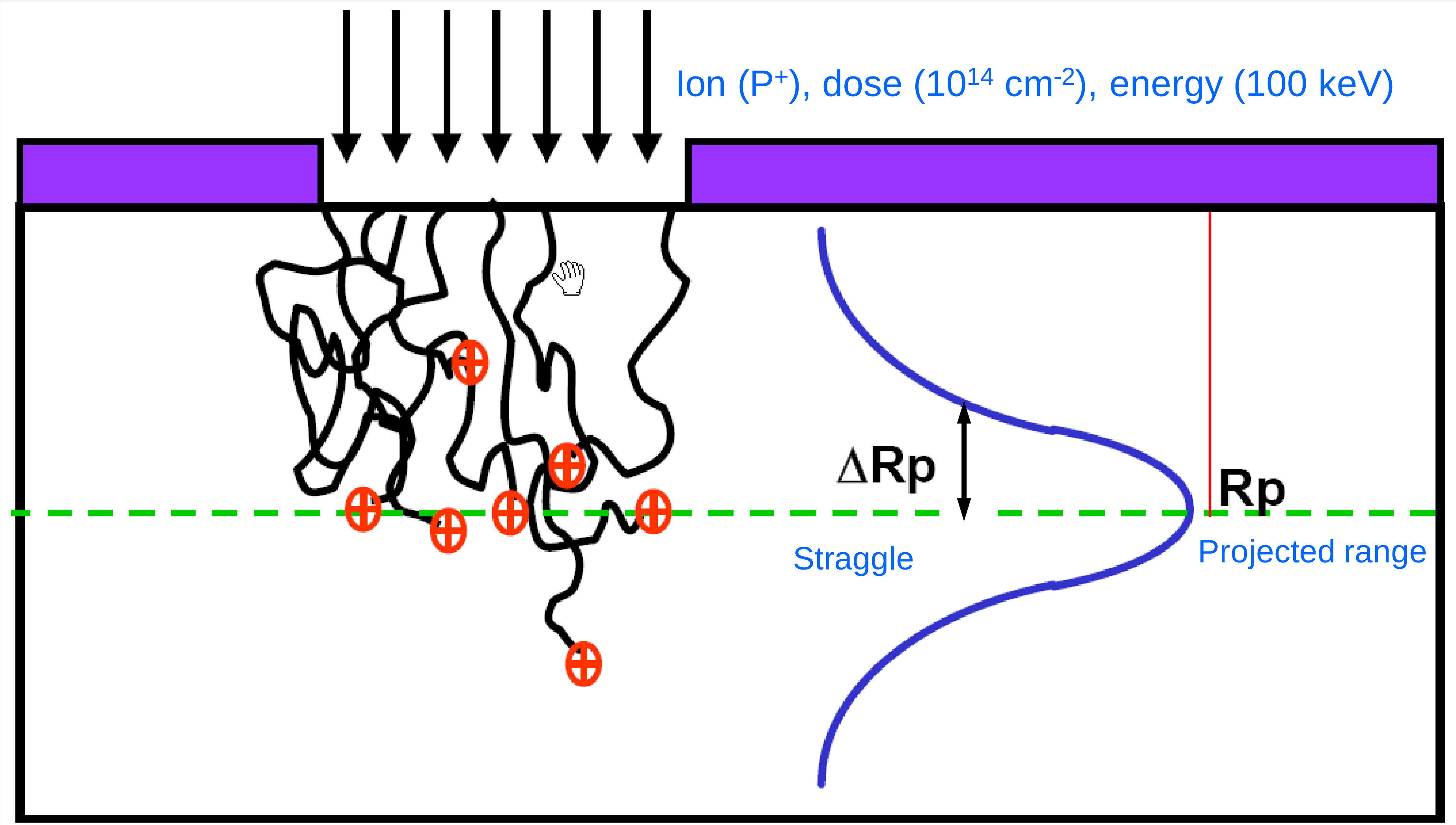
Selective implantation and dopant profile

Room temperature

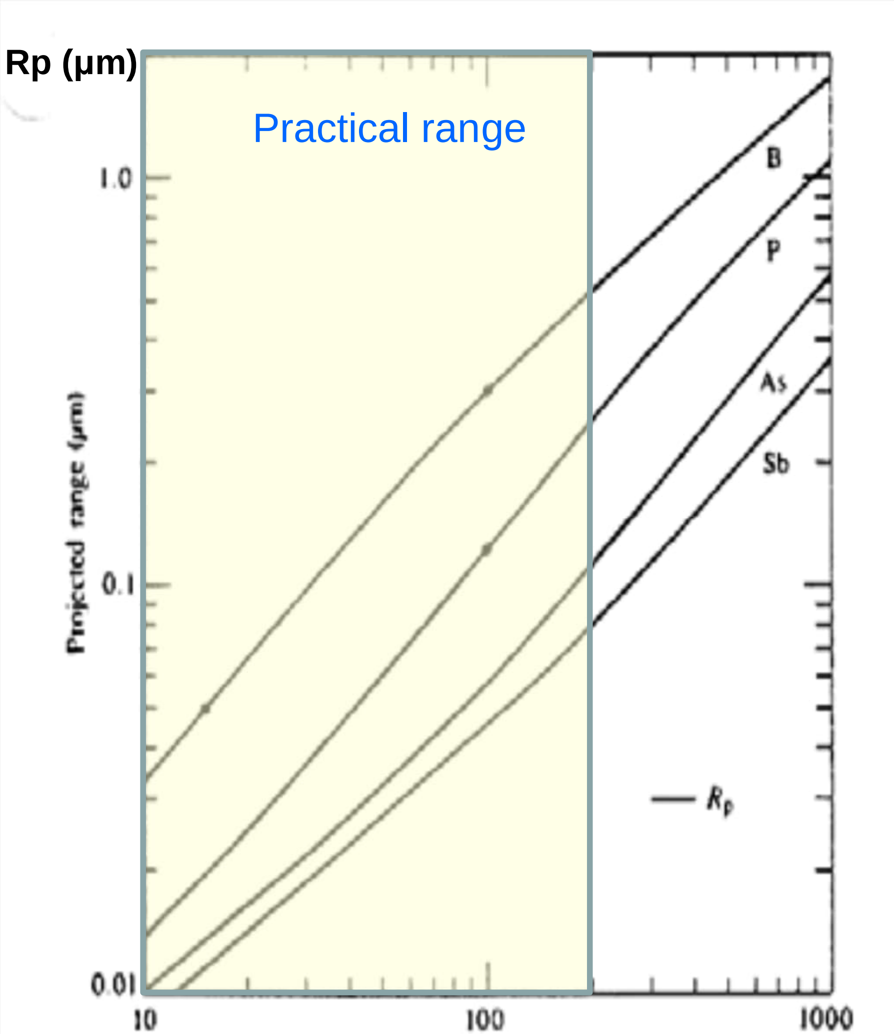


Maximum concentration is below the surface
Compare with diffusion!

Projected range and straggle



Projected range (R_p) in Si



Ion energy (keV)

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

Implantation damage

Can be removed by anneal at 1000°C during 30s

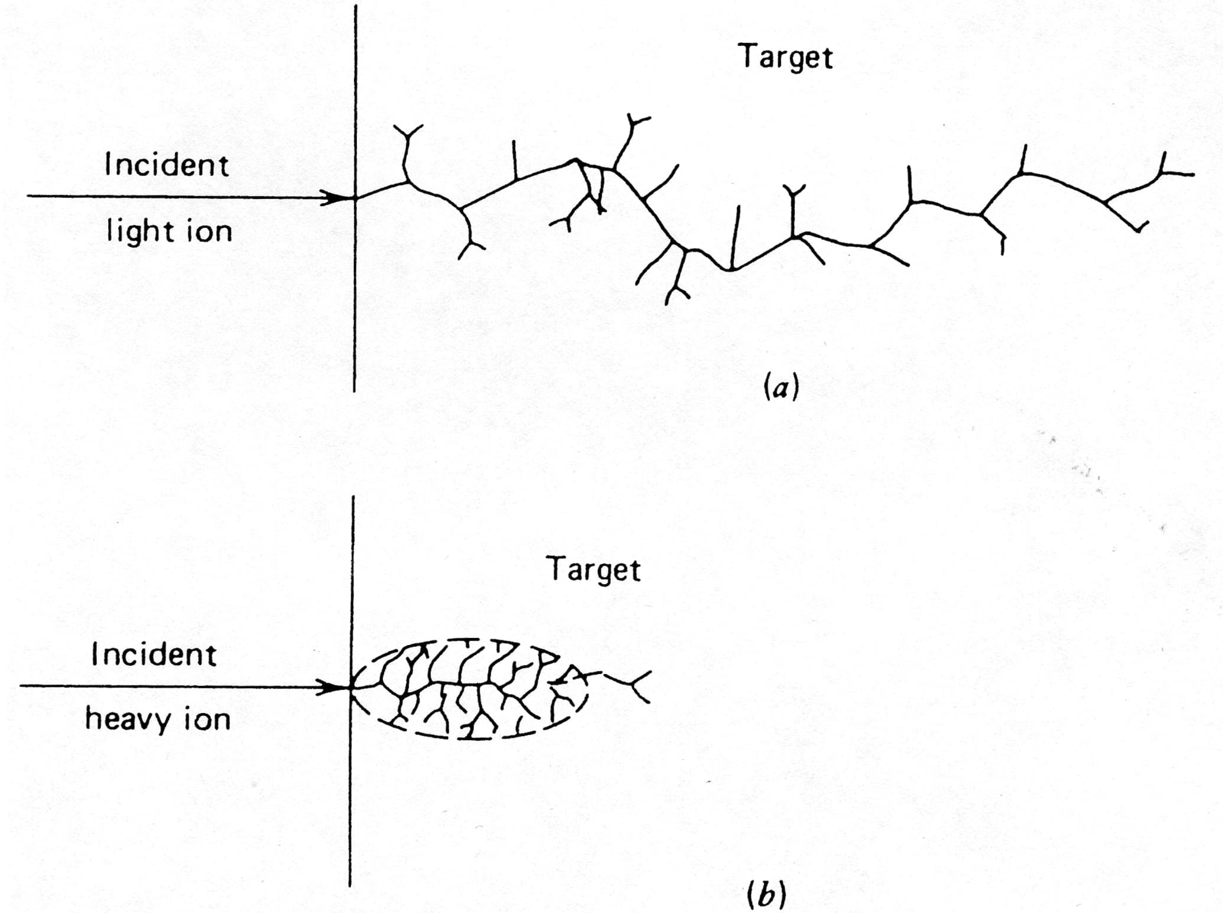
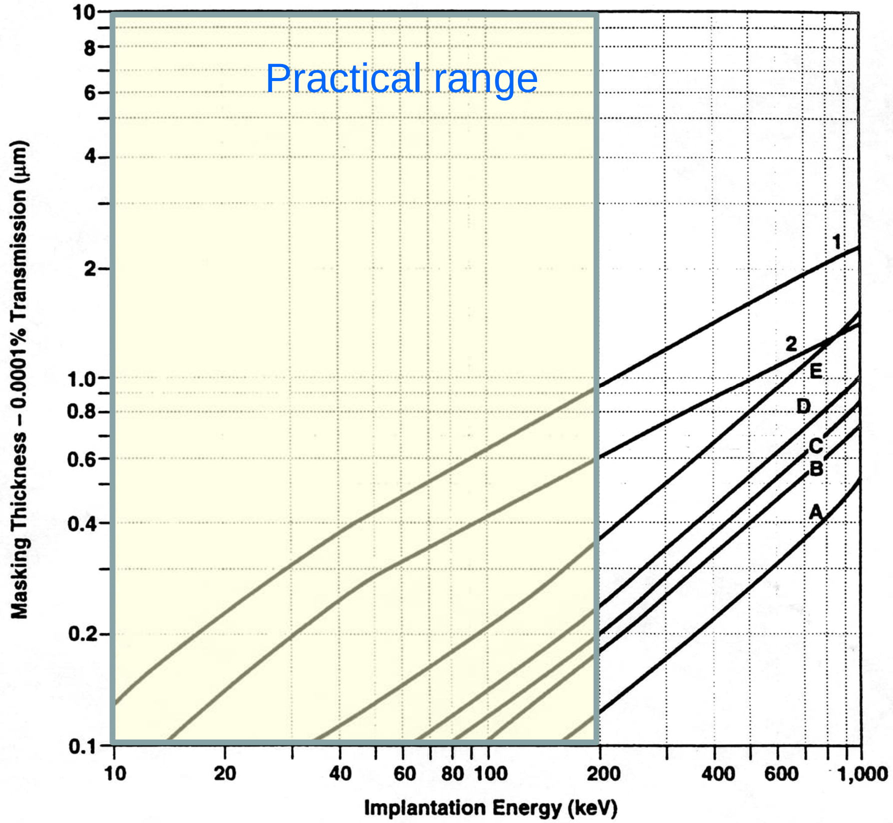


Fig. 6.18 Damage due to (a) light ions and (b) heavy ions.

Mask thickness for implantation

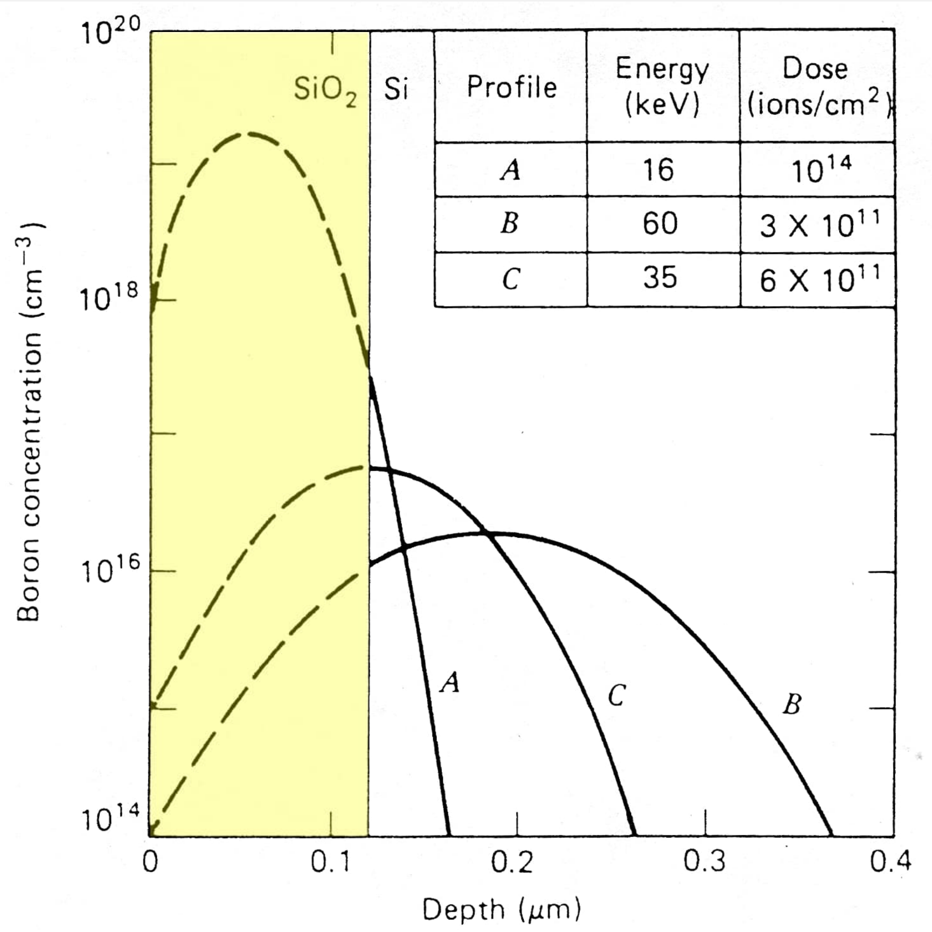


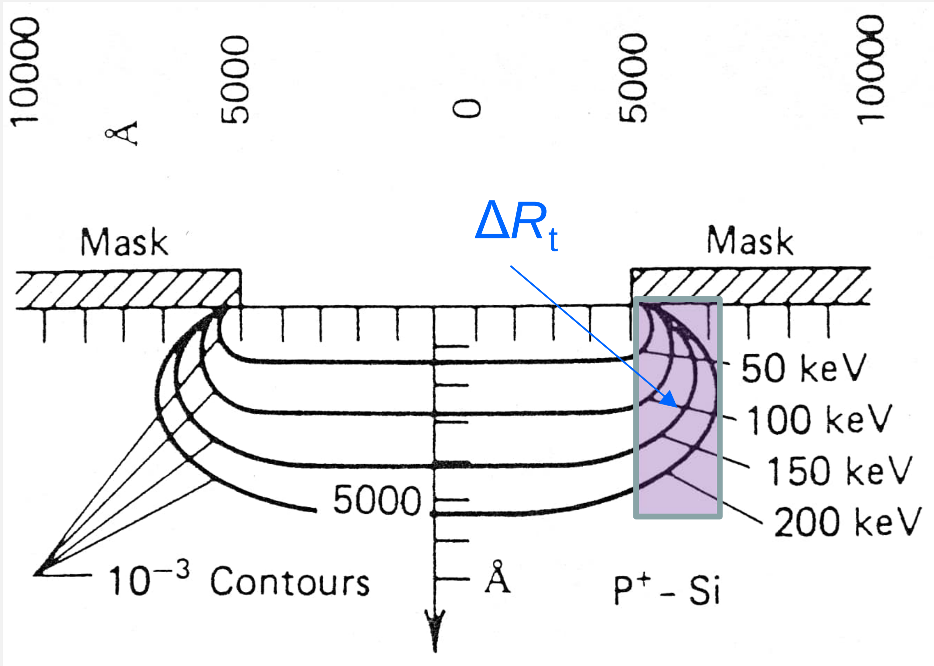
Ion	Curve	Masking Material	Ion	Curve	Masking Material
Boron (Top)	1	Thermal SiO_2, Polysilicon, Aluminum, Negative Resist, or Positive Resist.	Antimony (Bottom)	A	CVD Si_3N_4
				B	Thermal SiO_2 or Aluminum
				C	Polysilicon
	2	CVD Si_3N_4		D	Negative Resist
				E	Positive Resist

Source: Technology Associates 14666

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

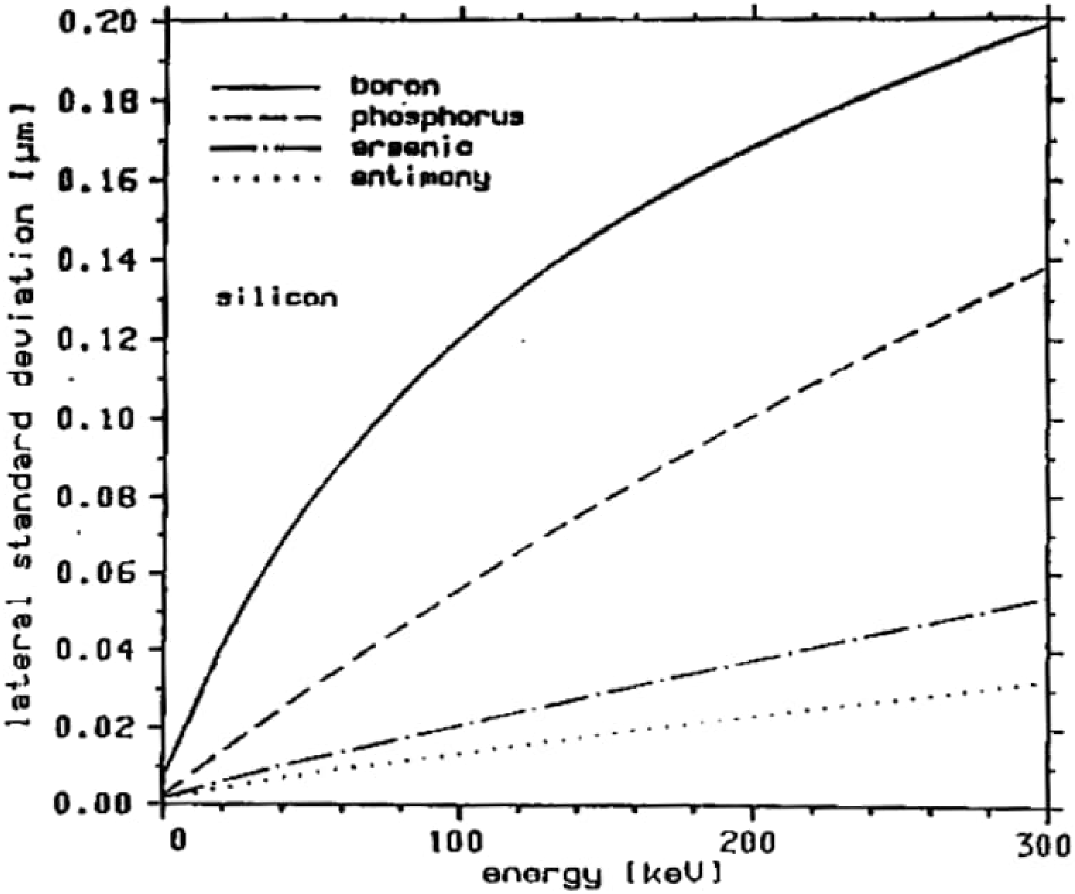
Simulated implantation profiles



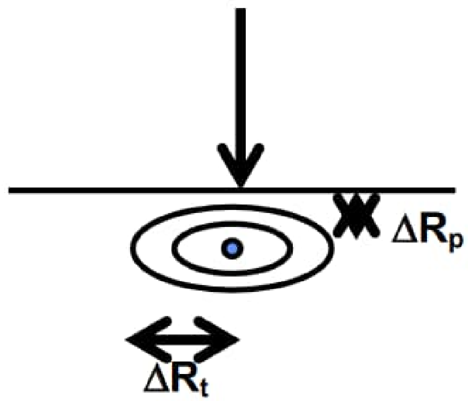


Lateral straggle ΔR_t

ΔR_t



Lateral standard deviation of boron, phosphorus, arsenic and antimony in silicon



http://www-inst.eecs.berkeley.edu/~ee143/fa16/lectures/Lecture07-Ion%20Implantation.pdf

Measured implantation profiles

Boron | Phosphorus

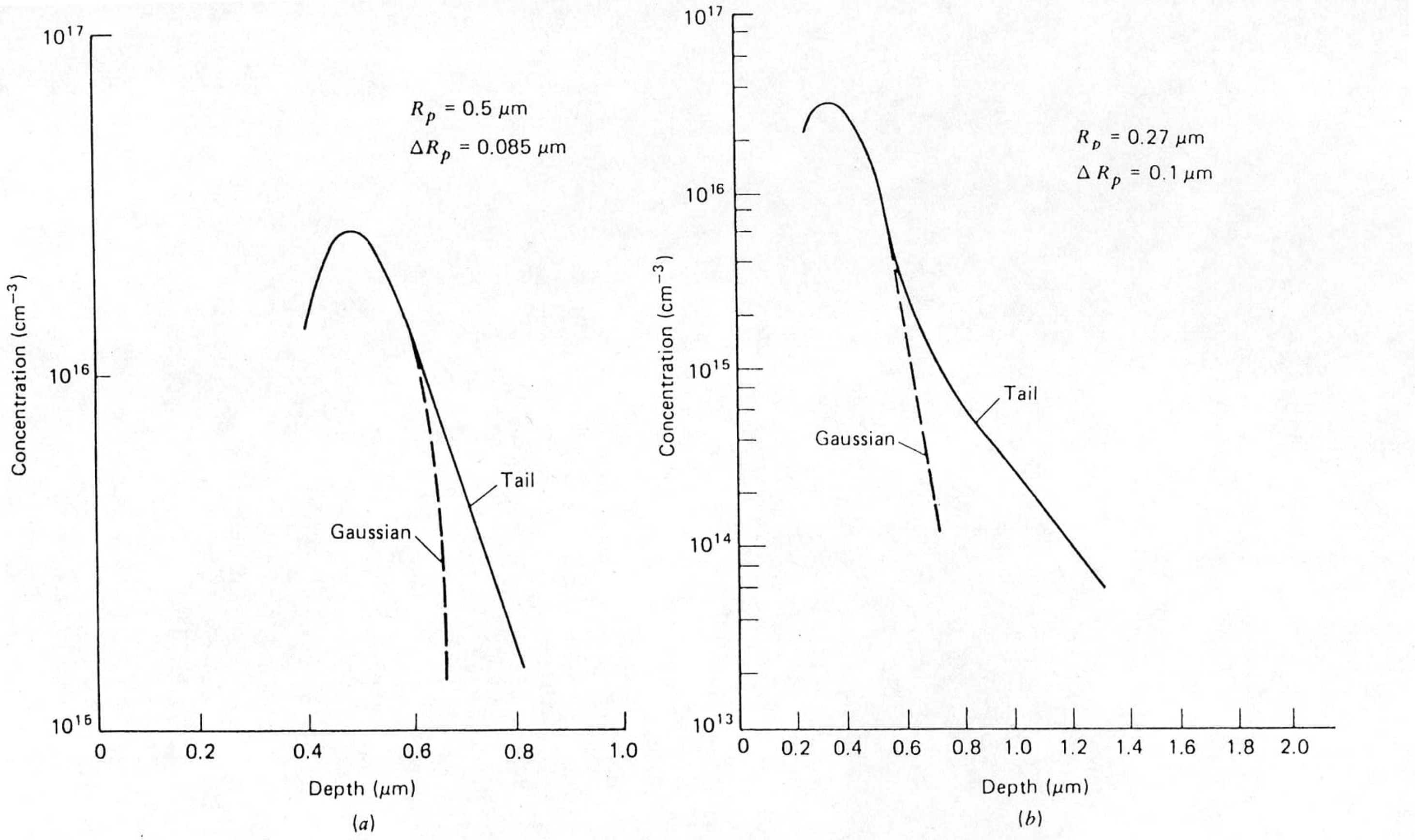


Fig. 6.3 Ion concentration. (*a*) Boron in silicon, 250-keV ions, annealed at 850°C for 30 min. Adapted from Moline [5]. (*b*) Phosphorus in silicon, 300-keV ions, annealed at 800°C for 30 min. Adapted from Dearnaley et al. [3].

Implantation parameters

Ion energies 10-200 keV

Implantation depths 10-500 nm

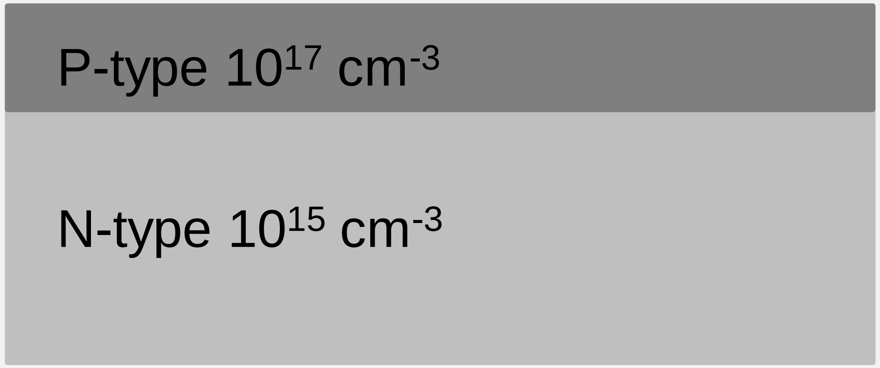
Doses 10^{11} to 10^{16} ions/cm^2, what corresponds concentrations ca. 10^{15} cm^{-3} to 10^{20} cm^{-3}.

$5 \cdot 10^{15}$ 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.

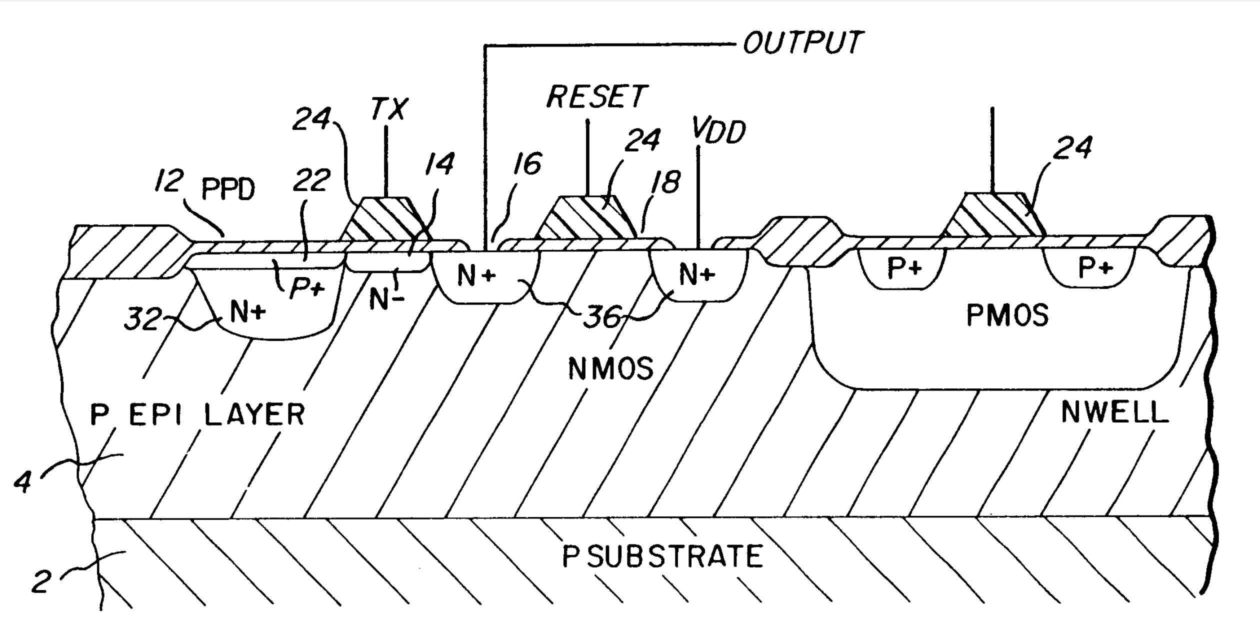
Diffusion and implantation can only **add** dopants ➔ doped region dopant concentration always higher than original wafer.



Possible

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:

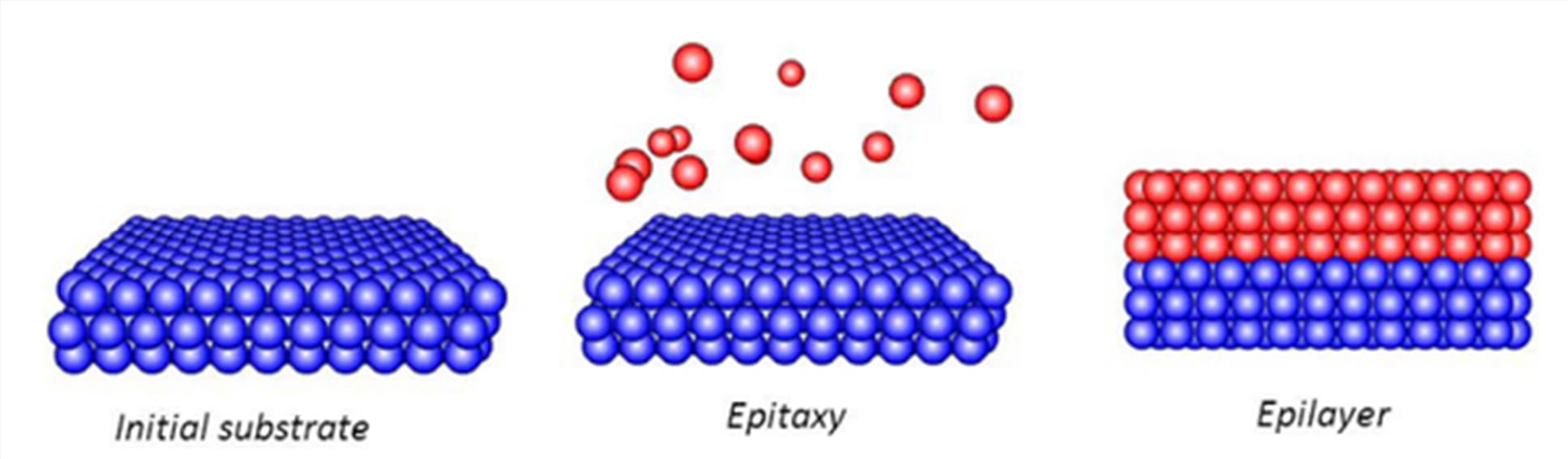
- more accurate and uniform in dose control
- produces greater variety of profiles
- possible through oxide and nitride
- provides wide selection of mask materials
- less sensitive to surface cleaning procedures

Implantation vs. diffusion

- Sideways spreading in diffusion ≈ depth
- Sideways spreading in implantation (ΔR_t) 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. 1000ºC
- Diffusion is the best for high doping level, deep junctions and double side doping

Epitaxy - "arranging upon"



Epitaxy conditions:

Substrate and film are single crystalline

Crystal lattices are closely matching

Atomically clean substrate surface

Doping can be done during film growth

Common epitaxy pairs (heteroepitaxy):

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

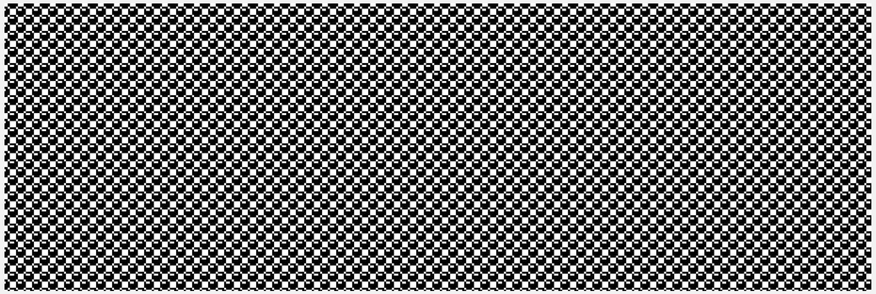
Sapphire wafer - Si, GaN

CeO_2 film – YBCO (yttrium barium copper oxide)

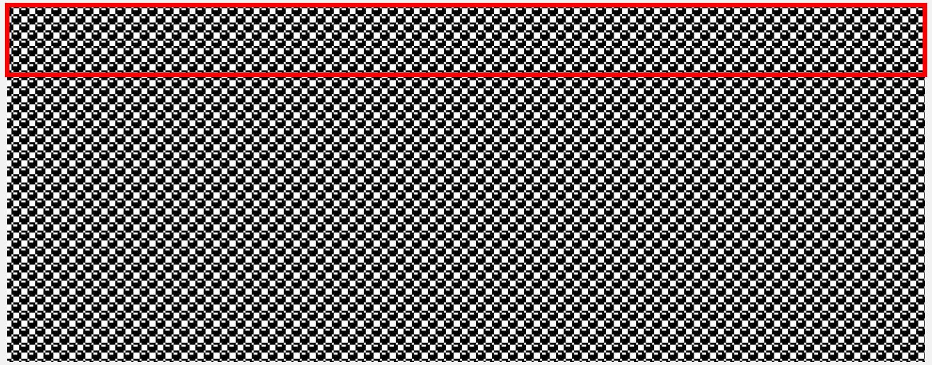
GaAs wafer – GaAlAs/GaAs

Homoepitaxy

Crystalline film A on top a crystalline wafer A



Single crystal wafer

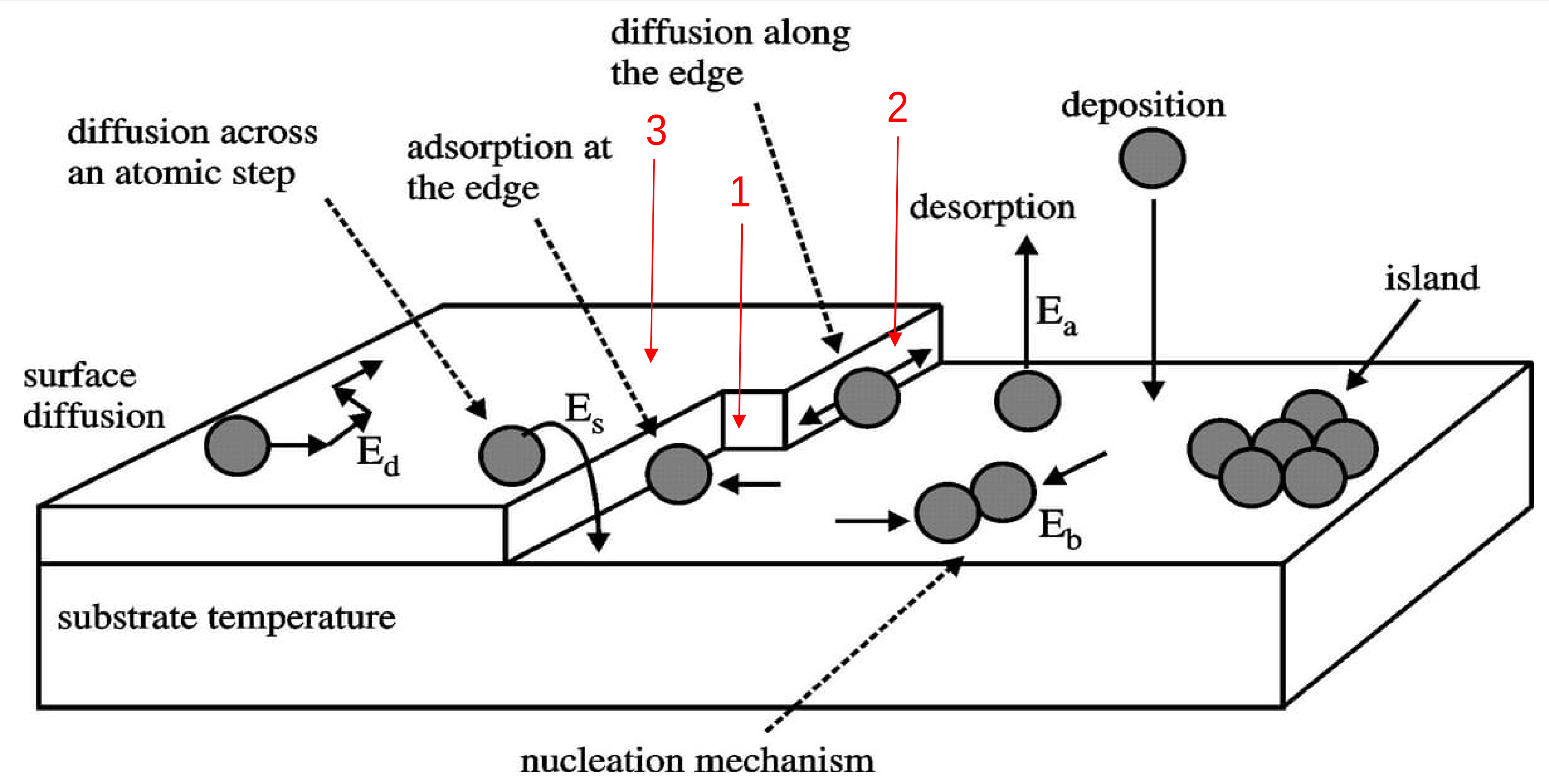


Epitaxial layer of the same material deposited on top

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

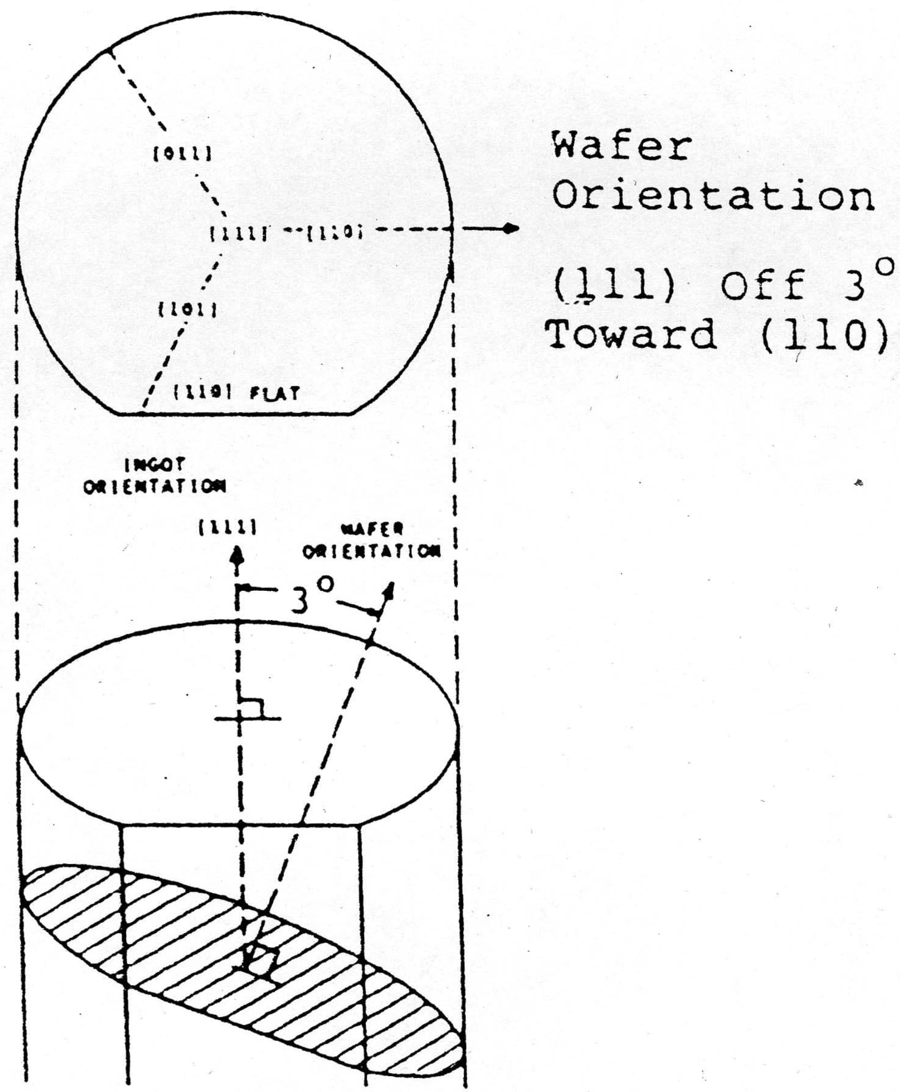
1. Freedom in the order of doping
2. Absence of O_2 and C contaminations

Preferable nucleation places: kink growth model



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

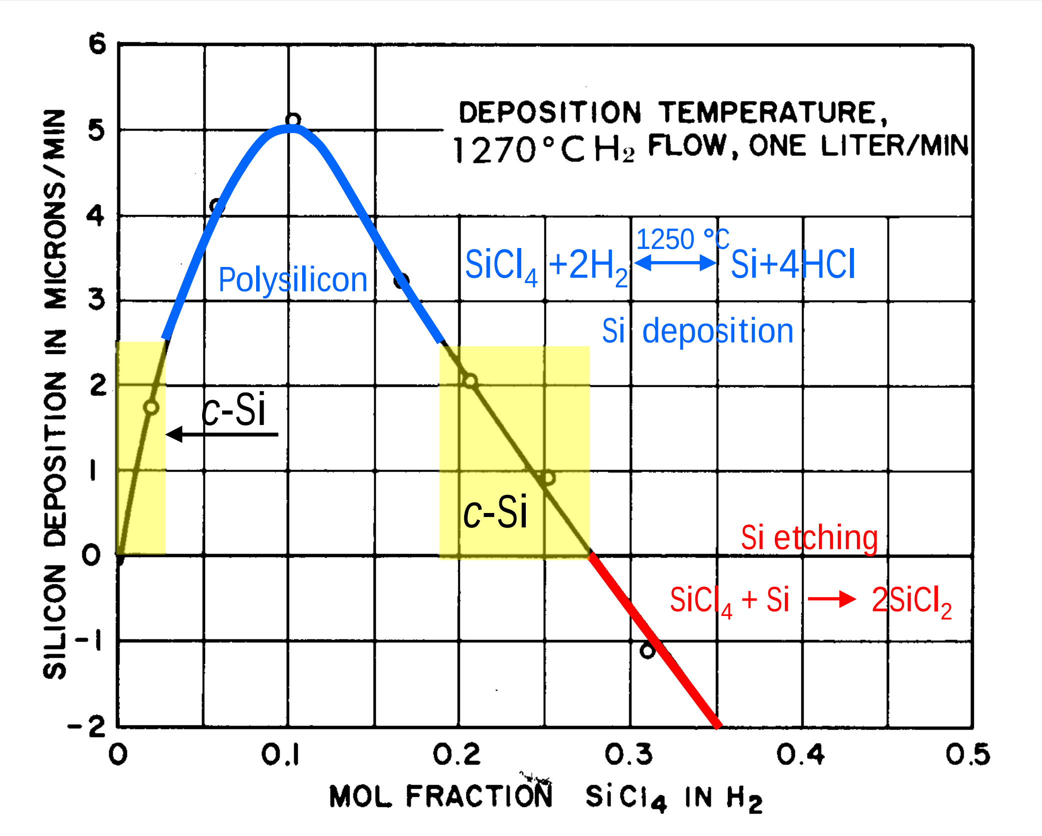
Miscutting of (111) wafers for epitaxy

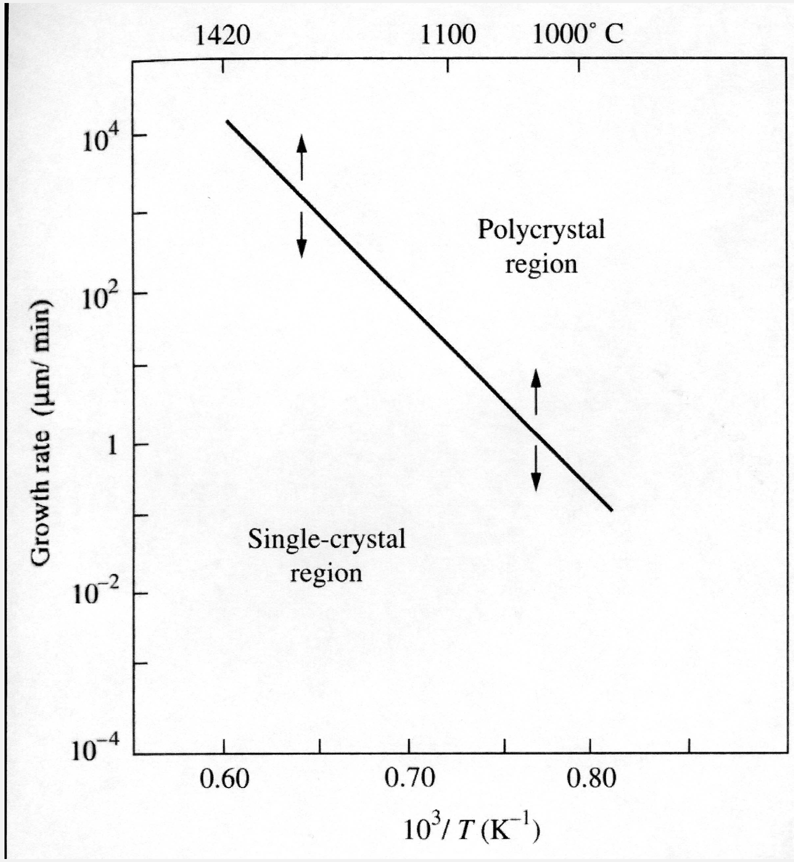


(111) WAFER-CUT OFF-ORIENTATION.

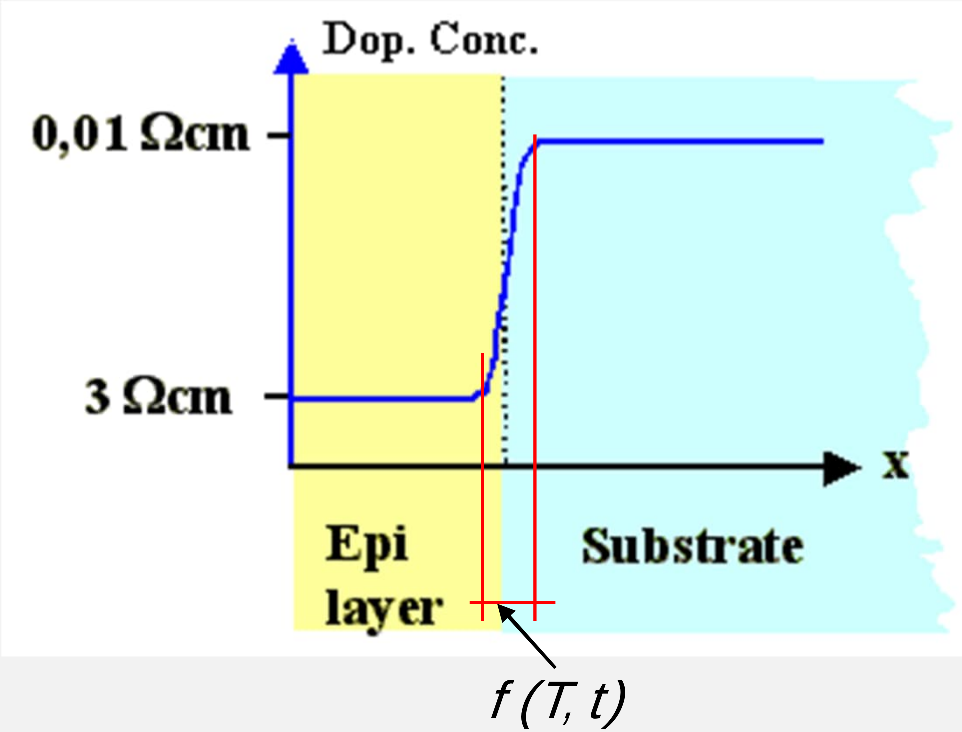
Vapor-Phase Epitaxy (VPE)

VPE is modified CVD





Dopant diffusion during epi



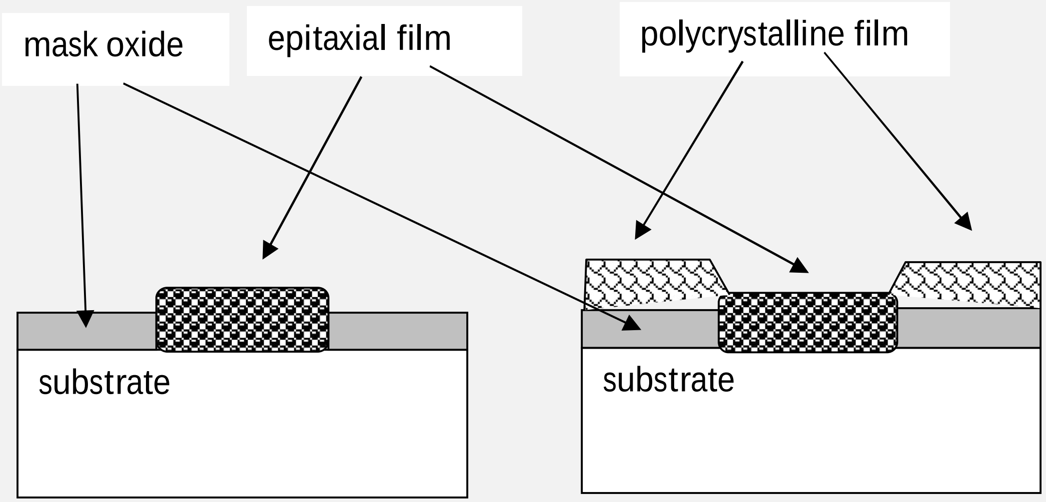
Lightly doped epi   Heavily doped substrate

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

Dopant diffusion from high concentration to low concentration.

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

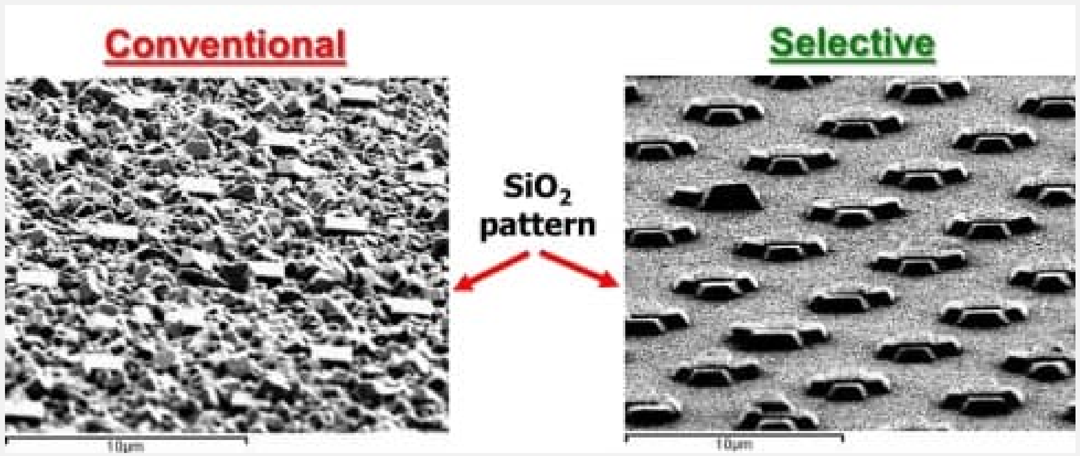
Selective epitaxy



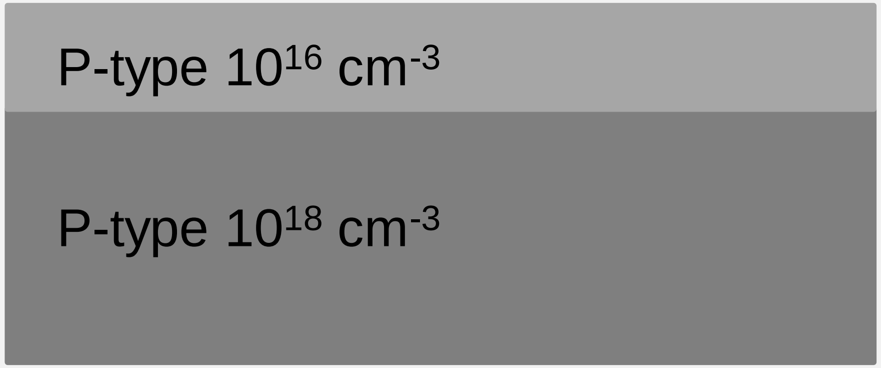
No deposition on oxide

Blanket deposition

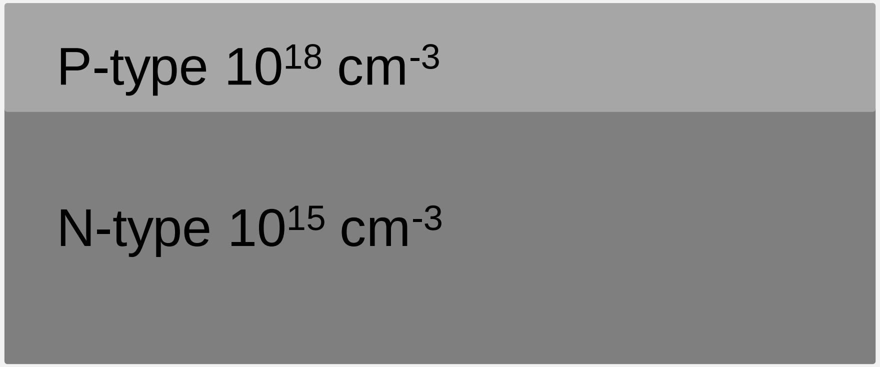
GaN on c-Si (100)



Doping and epitaxy



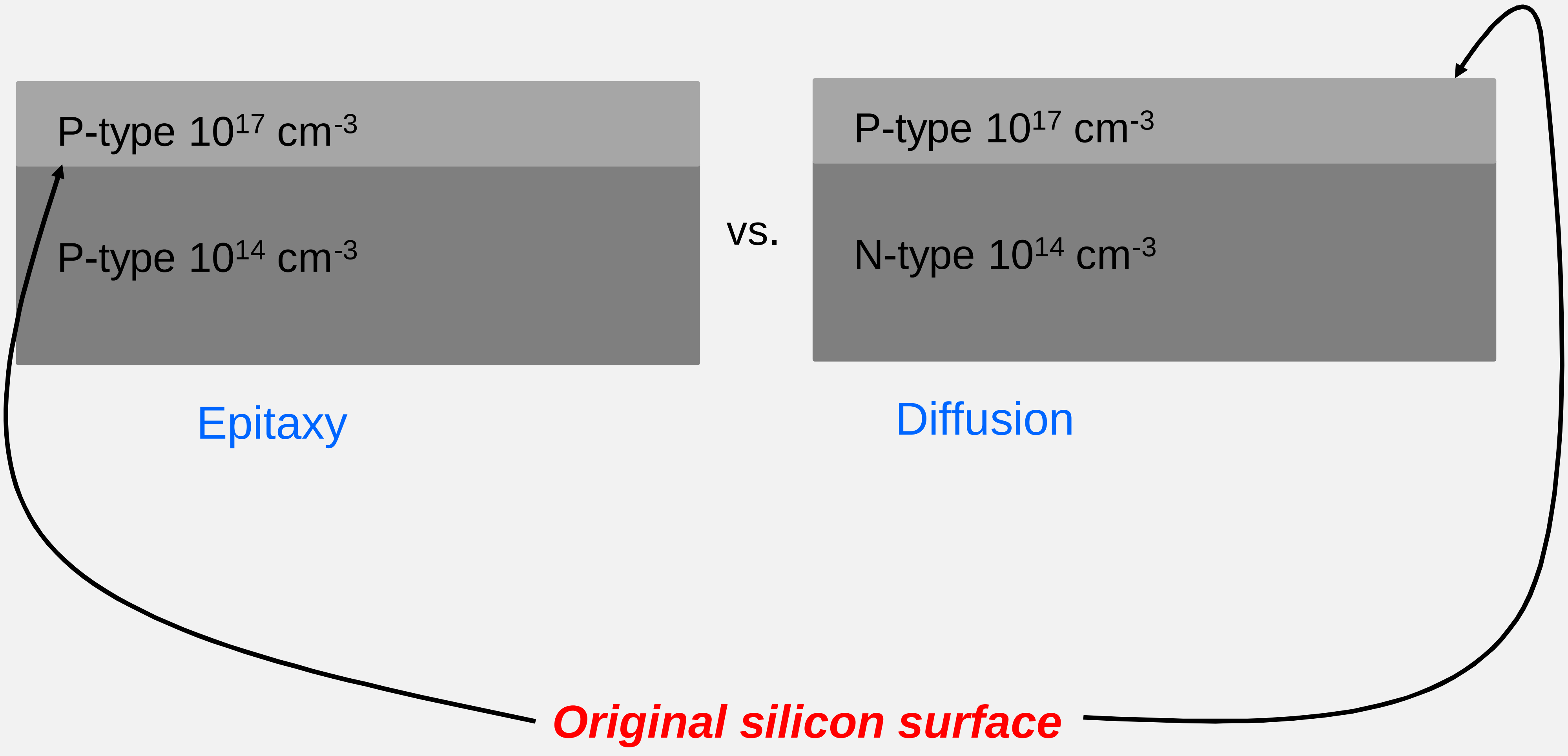
vs.



Epitaxy is the only way to get this.

Thick doped layer or uniform dopant profile.

Epitaxial layer vs. diffused layer



Epitaxy advantages

- 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