

PSI-5761 Introdução aos Processos de Fabricação em Microeletrônica

Aula05 – Dopagem: Difusão Térmica e Implantação Iônica

Laboratório de
Microeletrônica
Escola Politécnica
Universidade de São Paulo

Prof. Roberto K. Onmori sala C2-70 (tel. + 55 11 3091 5251)
email: rkonmori@lme.usp.br ou onmori@usp.br

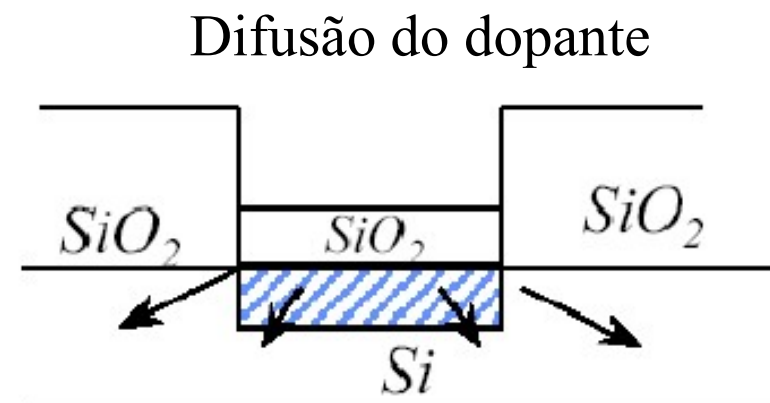
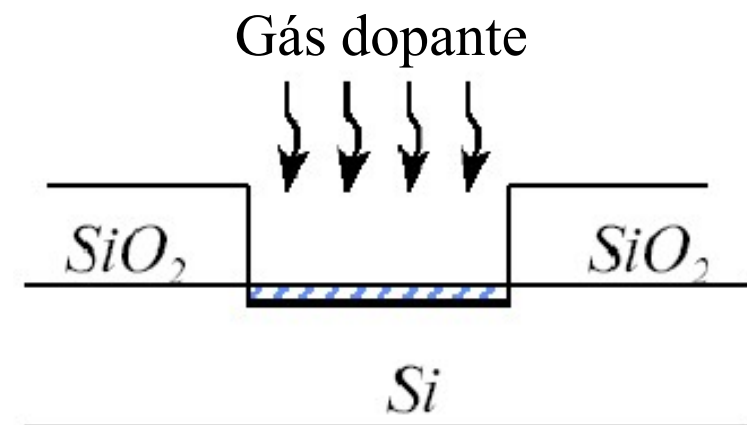
Prof. Fernando J. Fonseca sala C2-65 (tel. + 55 11 3091 0730)
email: Fernando.epusp@gmail.com.br

Introdução

- Historicamente, necessidade de introduzir impurezas por difusão para obter regiões do tipo n (P, As) ou p (B) no silício.

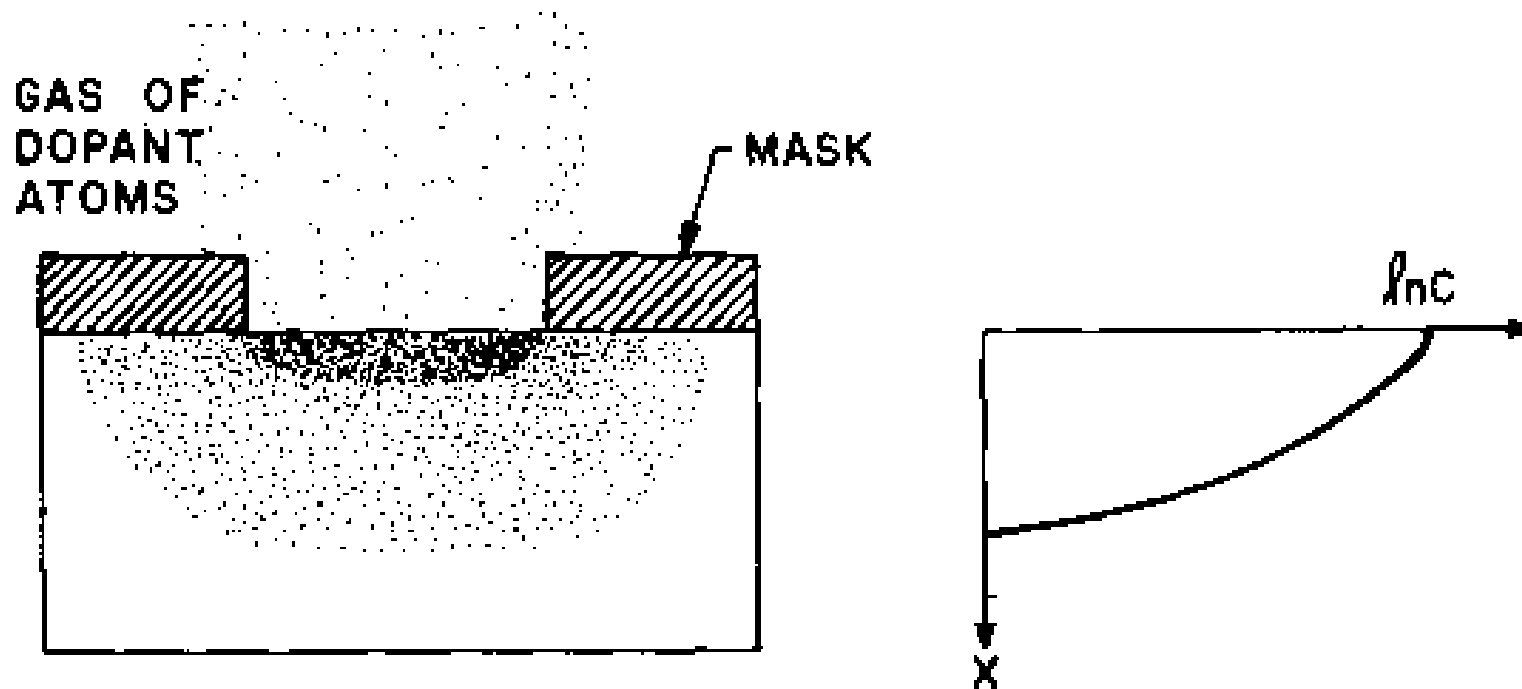
- Dopagem é a exposição da lâmina de Si em uma fonte contendo P, As ou B (deposição) e

- e a sua difusão em alta temperatura



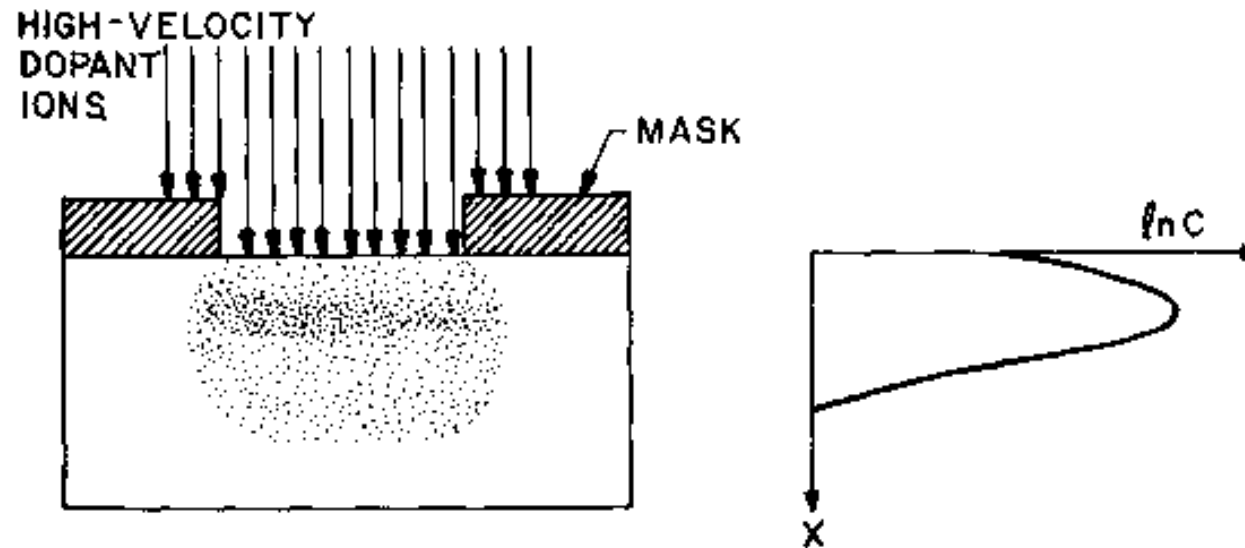


- Até 1970, uso de deposição em elevadas temperaturas em fase gasosa.
 - Perfil da deposição:



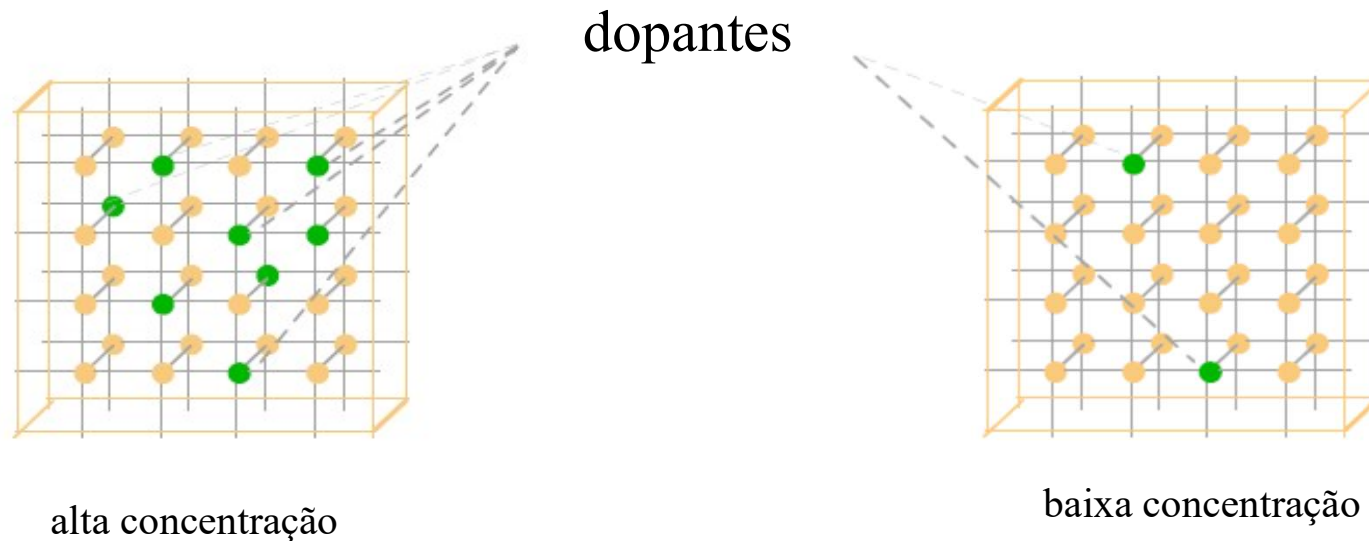


- A partir de 1970, o processo de dopagem passou a ser via implantação iônica com o seguinte aspecto:



Processo de Difusão Térmica

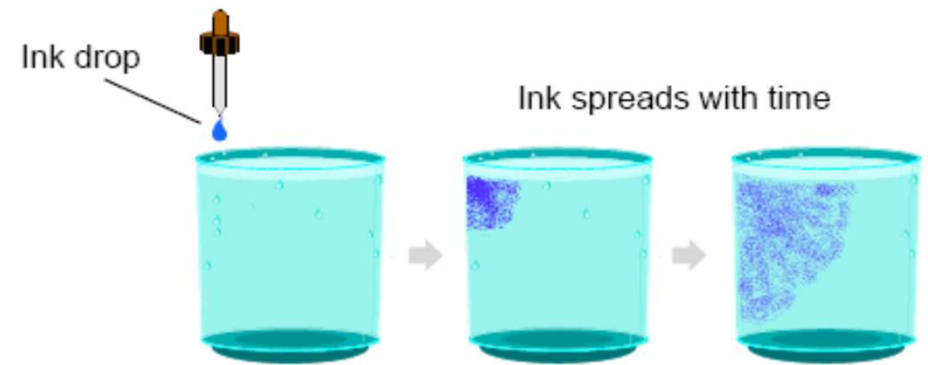
- Acontece com altas temperaturas: 600-1200 °C;
- Obedece a Equação de Fick;
- Apresenta um perfil de Difusão característico;
- Máscaras para a Difusão





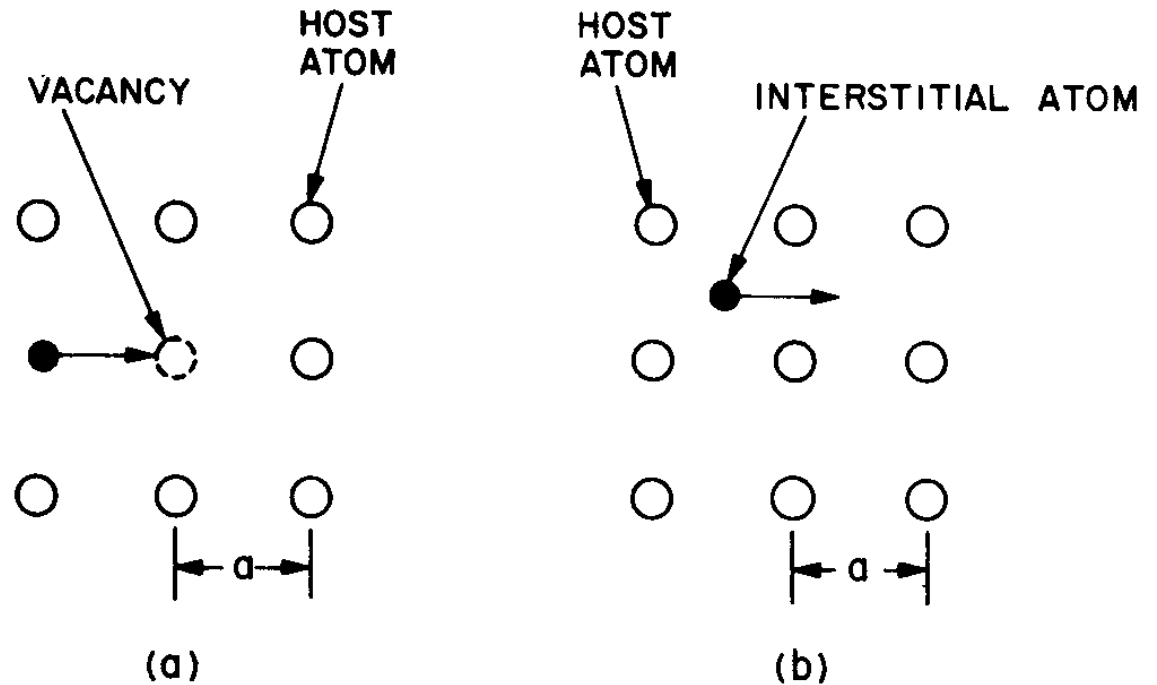
Equação de Fick

1855 – teoria da difusão



Flux of ink $\rightarrow F = -D \frac{\partial C(x,t)}{\partial x}$ driving force

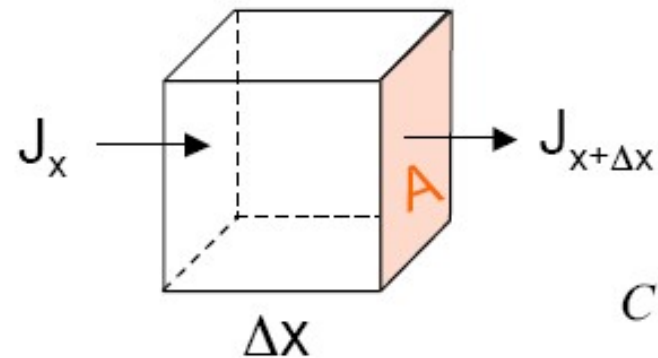
Proportionality constant (Diffusion coefficient) \nearrow



Models of atomic diffusion mechanisms for a two-dimensional lattice, where a is the lattice constant. (a) Vacancy mechanism. (b) Interstitial mechanism.¹

Balanço de Massa

{Fica acumulado} = {entrada} - {saída}



$$C \equiv \left[\frac{\#}{\text{cm}^3} \right]$$

$$C_{t+\Delta t} A \Delta x - C_t A \Delta x = J_x A \Delta t - J_{x+\Delta x} A \Delta t$$

$$J \equiv \left[\frac{\#}{\text{cm}^2 \text{ s}} \right]$$

$$\frac{C_{t+\Delta t} - C_t}{\Delta t} = - \frac{J_{x+\Delta x} - J_x}{\Delta x}$$



$$\boxed{\frac{\partial C}{\partial t} = - \frac{\partial J}{\partial x}}$$



Modelo para 1 D

$$\frac{\partial C(x,t)}{\partial t} = -\frac{\partial J(x,t)}{\partial x} \quad \& \quad J = -D \frac{\partial C(x,t)}{\partial x}$$

$$G_n = R_n = 0$$

Fick's diffusion equation.
$$\frac{\partial C(x,t)}{\partial t} = D \frac{\partial^2 C(x,t)}{\partial x^2}$$

diffusion coefficients
$$D = D_o \exp \left[\frac{-E_a}{kT} \right]$$

Necessita de 1 condição inicial e 2 condições de contorno

Perfil de difusão

$$C(x, 0) = 0 \quad C(0, t) = C_s \quad C(\infty, t) = 0$$

$$C(x, t) = C_s \operatorname{erfc} \left[\frac{x}{2\sqrt{Dt}} \right]$$

$$\operatorname{erf}(x) \equiv \frac{2}{\sqrt{\pi}} \int_0^x e^{-y^2} dy$$

$$\operatorname{erfc}(x) \equiv 1 - \operatorname{erf}(x)$$

$$\operatorname{erf}(0) = 0$$

$$\operatorname{erf}(\infty) = 1$$

$$\operatorname{erf}(x) \cong \frac{2}{\sqrt{\pi}} x \quad \text{for } x \ll 1$$

$$\operatorname{erfc}(x) \simeq \frac{1}{\sqrt{\pi}} \frac{e^{-x^2}}{x} \quad \text{for } x \gg 1$$

$$\frac{d}{dx} \operatorname{erf}(x) = \frac{2}{\sqrt{\pi}} e^{-x^2}$$

$$\frac{d^2}{dx^2} \operatorname{erf}(x) = -\frac{4}{\sqrt{\pi}} x e^{-x^2}$$

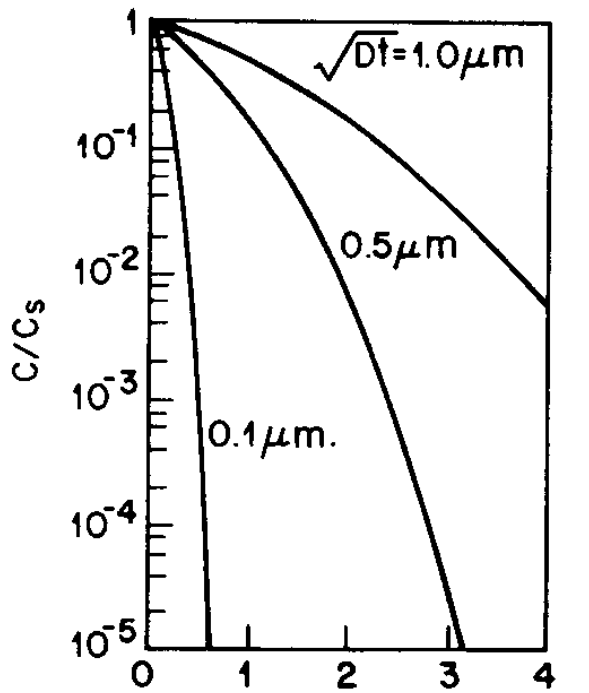
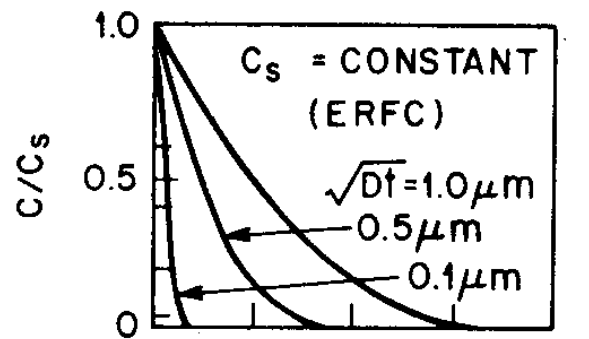
$$\int_0^x \operatorname{erfc}(y') dy' = x \operatorname{erfc}(x) + \frac{1}{\sqrt{\pi}} (1 - e^{-x^2})$$

$$\int_0^\infty \operatorname{erfc}(x) dx = \frac{1}{\sqrt{\pi}}$$

Table 1 Error Function Algebra



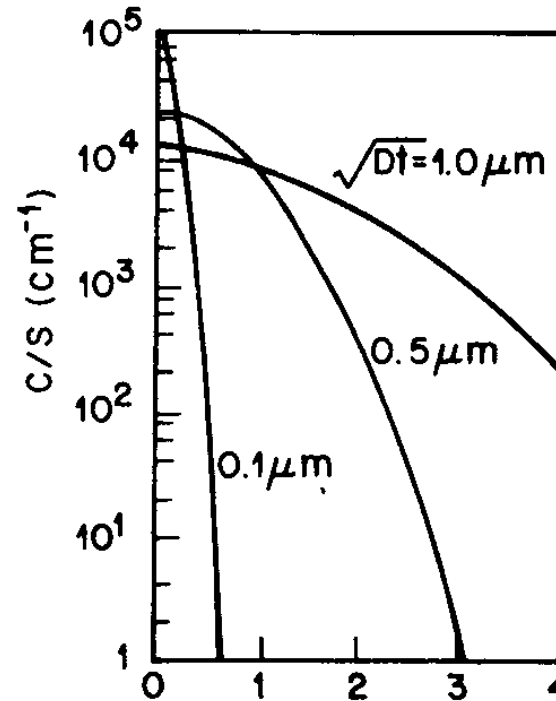
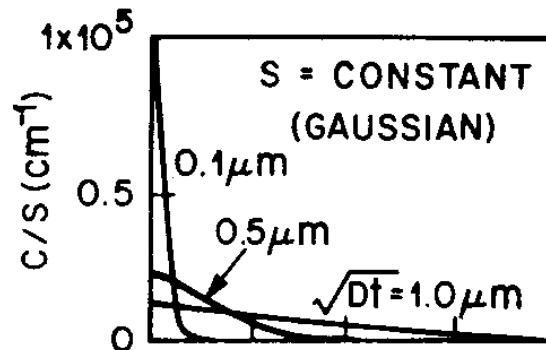
Fonte Infinita



DIFFUSION DEPTH x (μm)

(a)

Fonte Finita



DIFFUSION DEPTH x (μm)

(b)

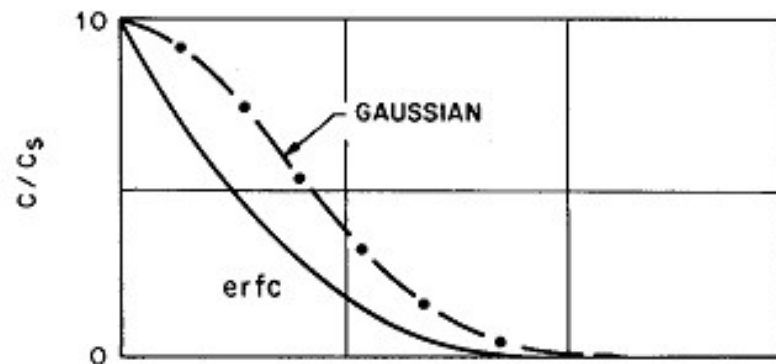
SixOyPz

SixOyBz

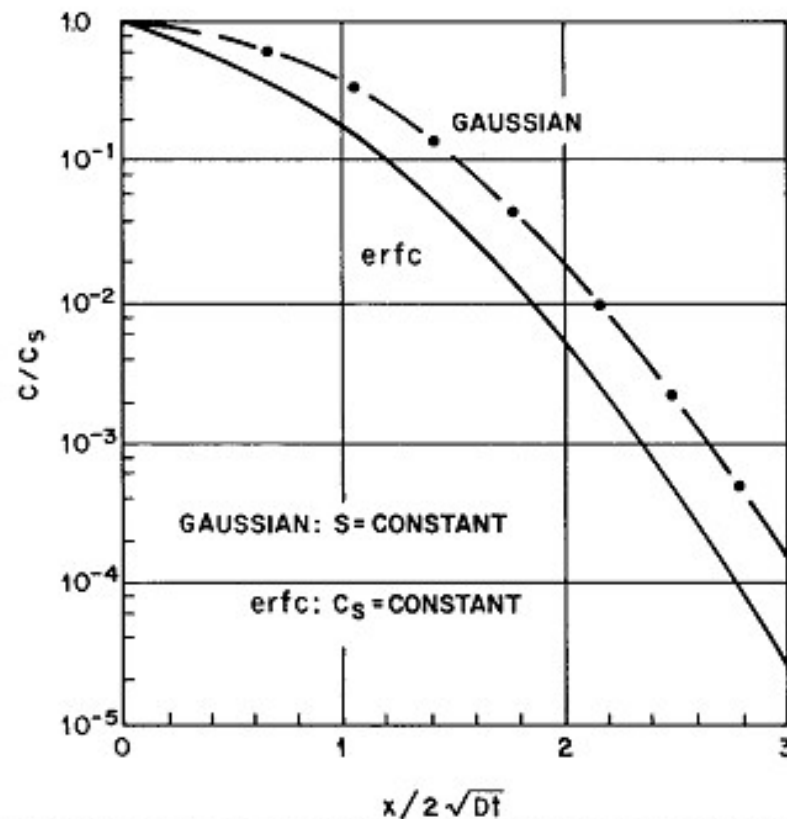
Fig. 4 Diffusion profiles. (a) Normalized complementary error function (erfc) versus distance for successive diffusion times. (b) Normalized Gaussian function versus distance for successive times.



Distribuição Gaussiana x erfc



Distribuição **erfc** para o processo de dopagem por difusão com **fonte infinita**



Distribuição **gaussiana** para o processo de dopagem com **fonte finita** (*Drive-in*)

Normalized concentration versus normalized distance for the erfc and the Gaussian function.

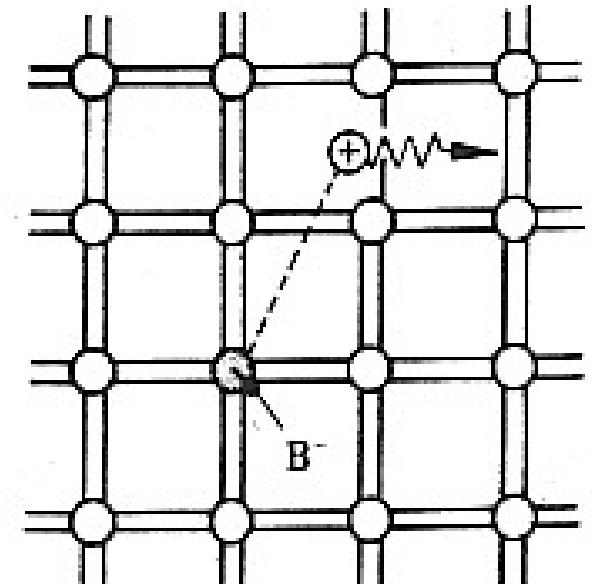
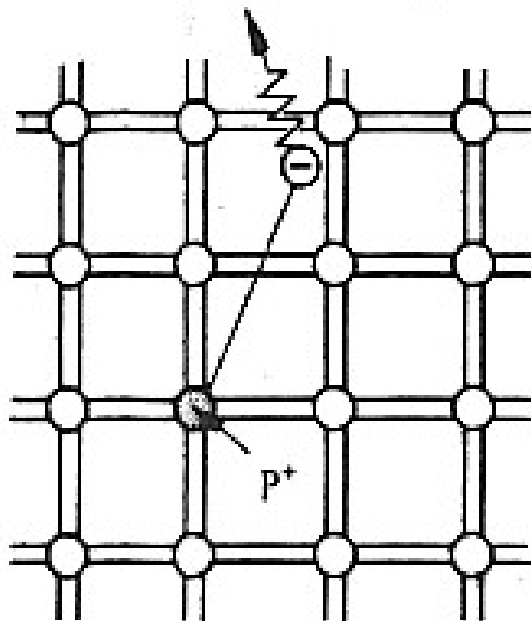
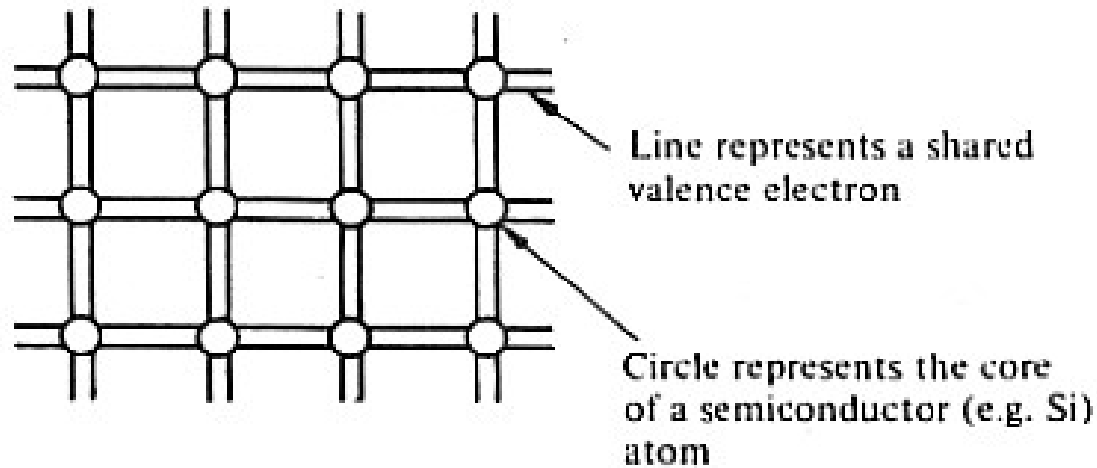


Donors (Electron-increasing Dopants)

Acceptors (Hole-increasing Dopants)

P \leftarrow }
As } Column V
Sb } elements

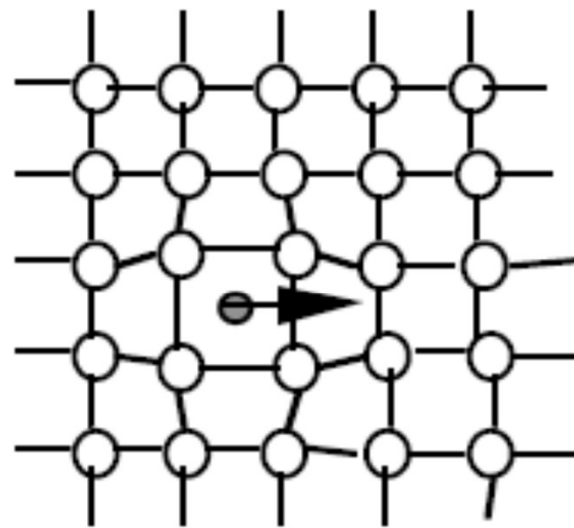
B \leftarrow }
Ga } Column III
In } elements
Al }





Intersticial

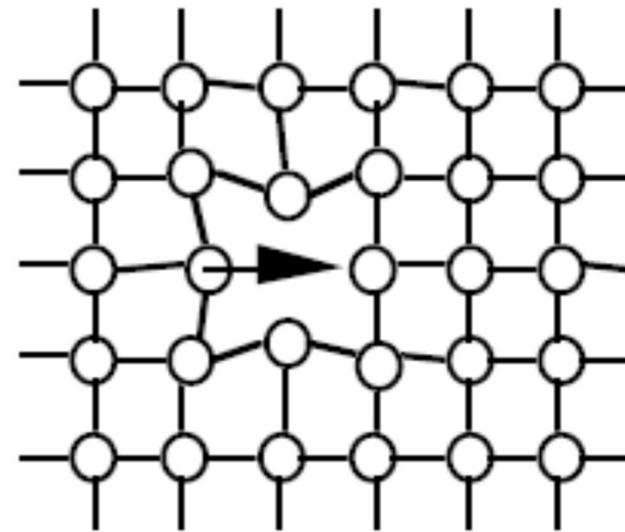
O, Cu, Au, Fe, Ni



$$E_A \approx 0.5 - 1 \text{ eV}$$

Vacância

P, B, As, Al, Ge, In

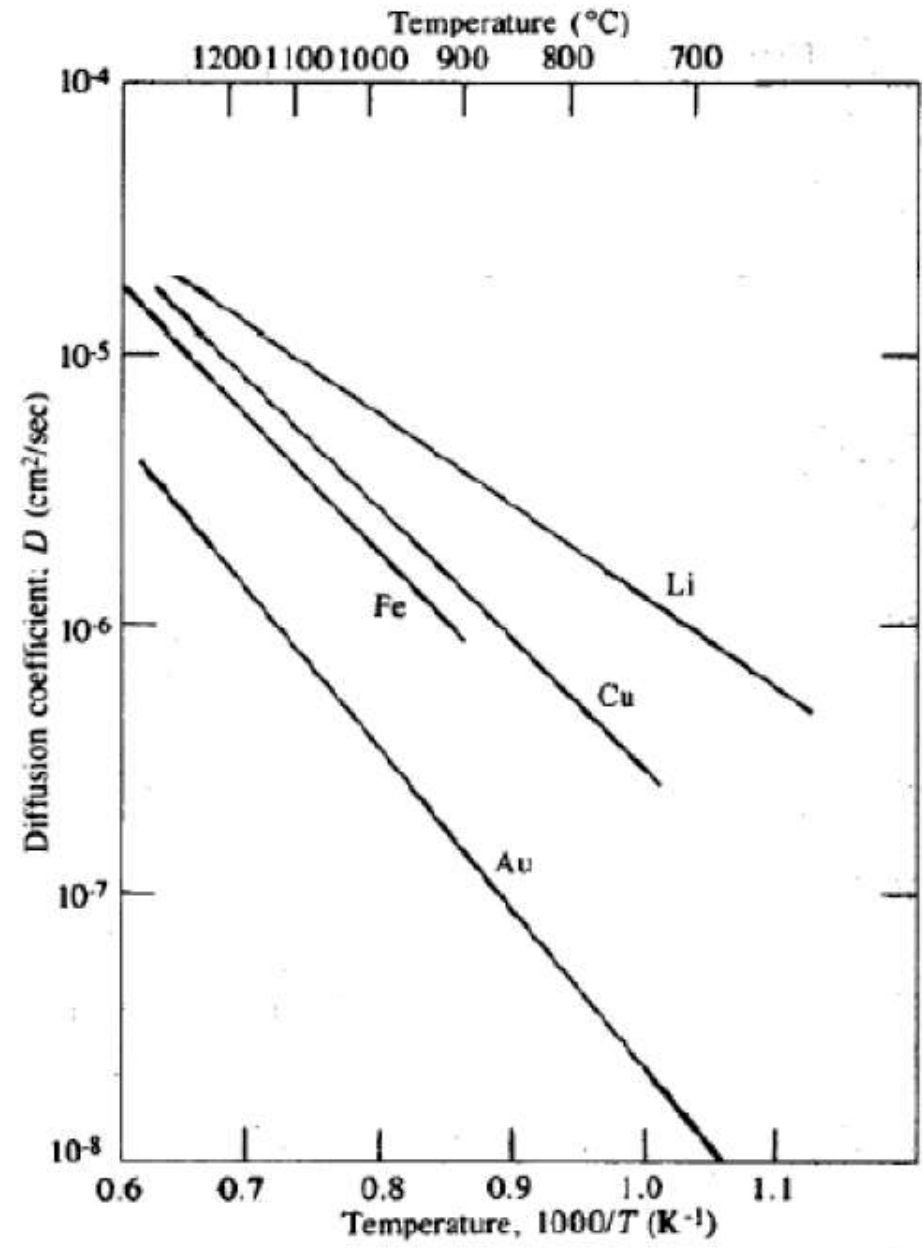
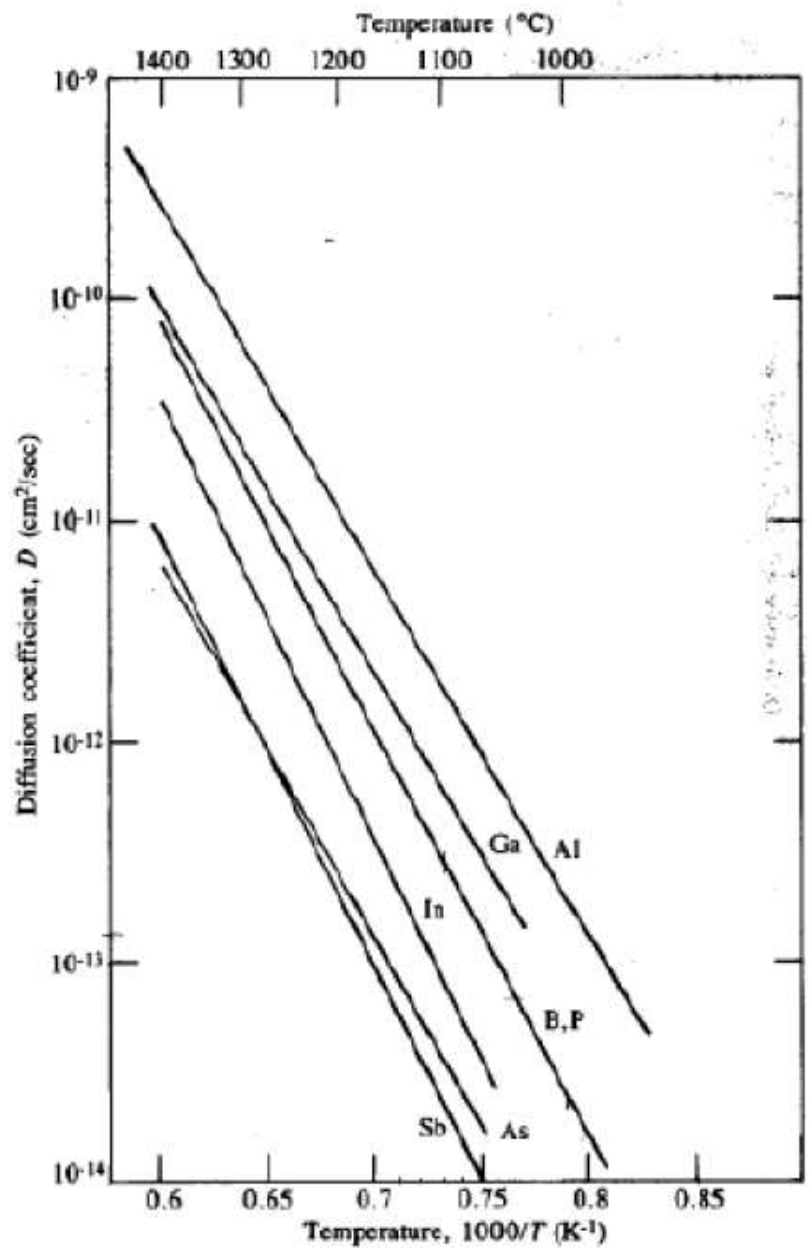


$$E_A \approx 3 - 4 \text{ eV}$$

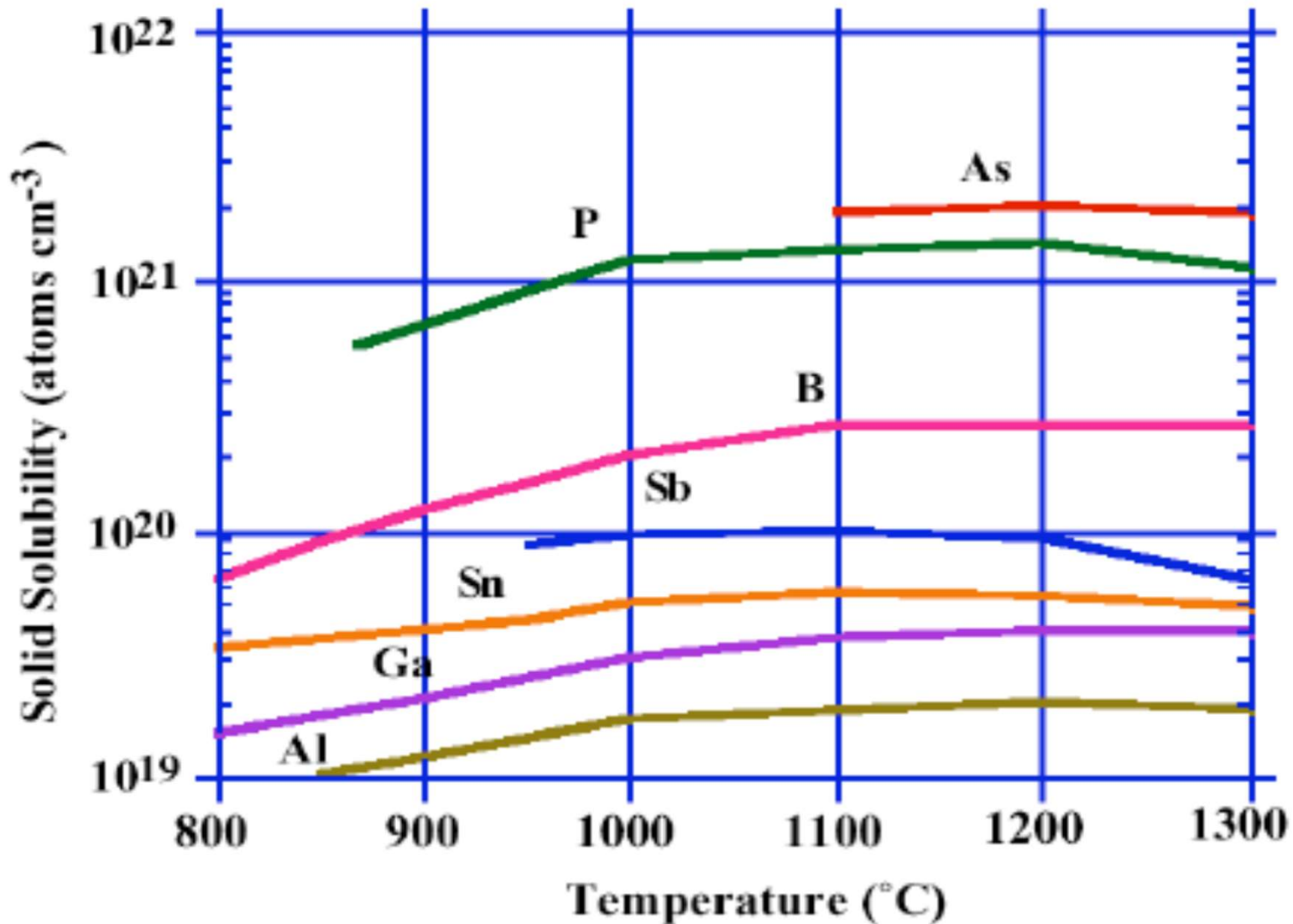


T	D
800 °C	10^{-16} cm ² /s
1200 °C	10^{-12} cm ² /s

Difusão no Silício



Solubilidade sólida



A Solubilidade Sólida é a concentração máxima possível para cada dopante em cada temperatura de difusão.



Difusão (*diffusion*)

$$\frac{\partial C(x,t)}{\partial t} = D \frac{\partial^2 C(x,t)}{\partial x^2}$$

IC $C(x,0) = 0$

BCs $C(0,t) = C_S$

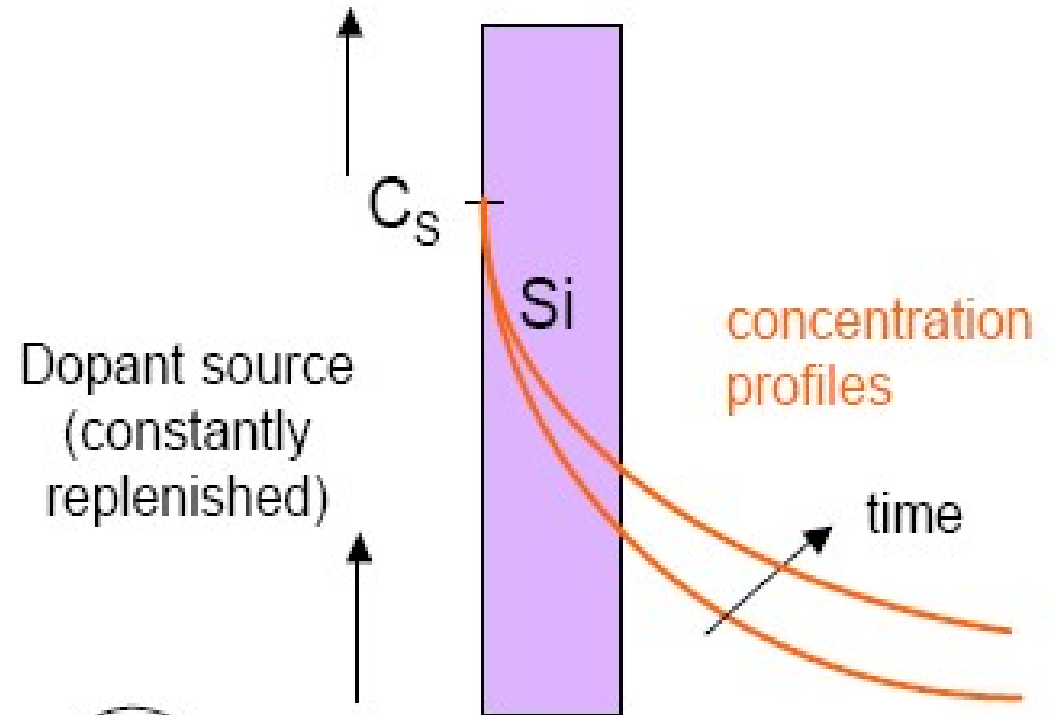
$$C(\infty,t) = 0$$

Solution:

$$C(x,t) = C_S \operatorname{erfc} \left[x / 2 \sqrt{Dt} \right]$$

complimentary error function

Diffusion length





Penetração (*Drive-in*)

$$\frac{\partial C(x,t)}{\partial t} = D \frac{\partial^2 C(x,t)}{\partial x^2}$$

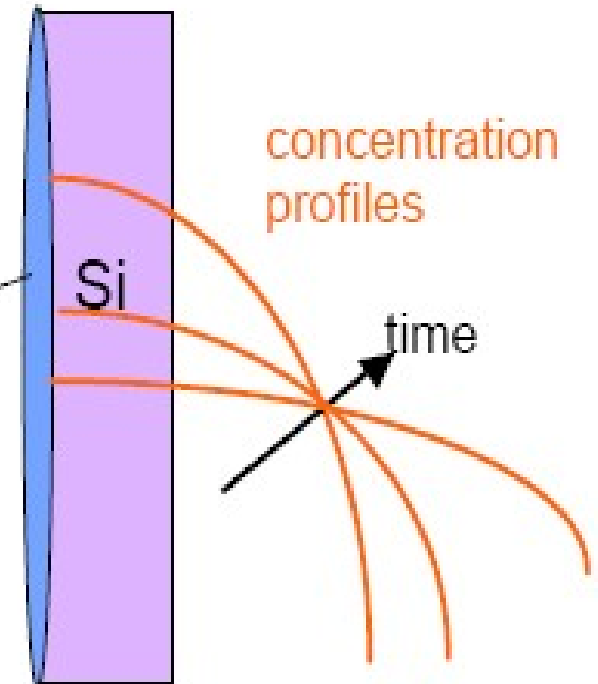
Dirac delta
function

IC $C(x,0) = Q_0 \delta(x)$

BCs $\frac{\partial C(0,t)}{\partial x} = 0$

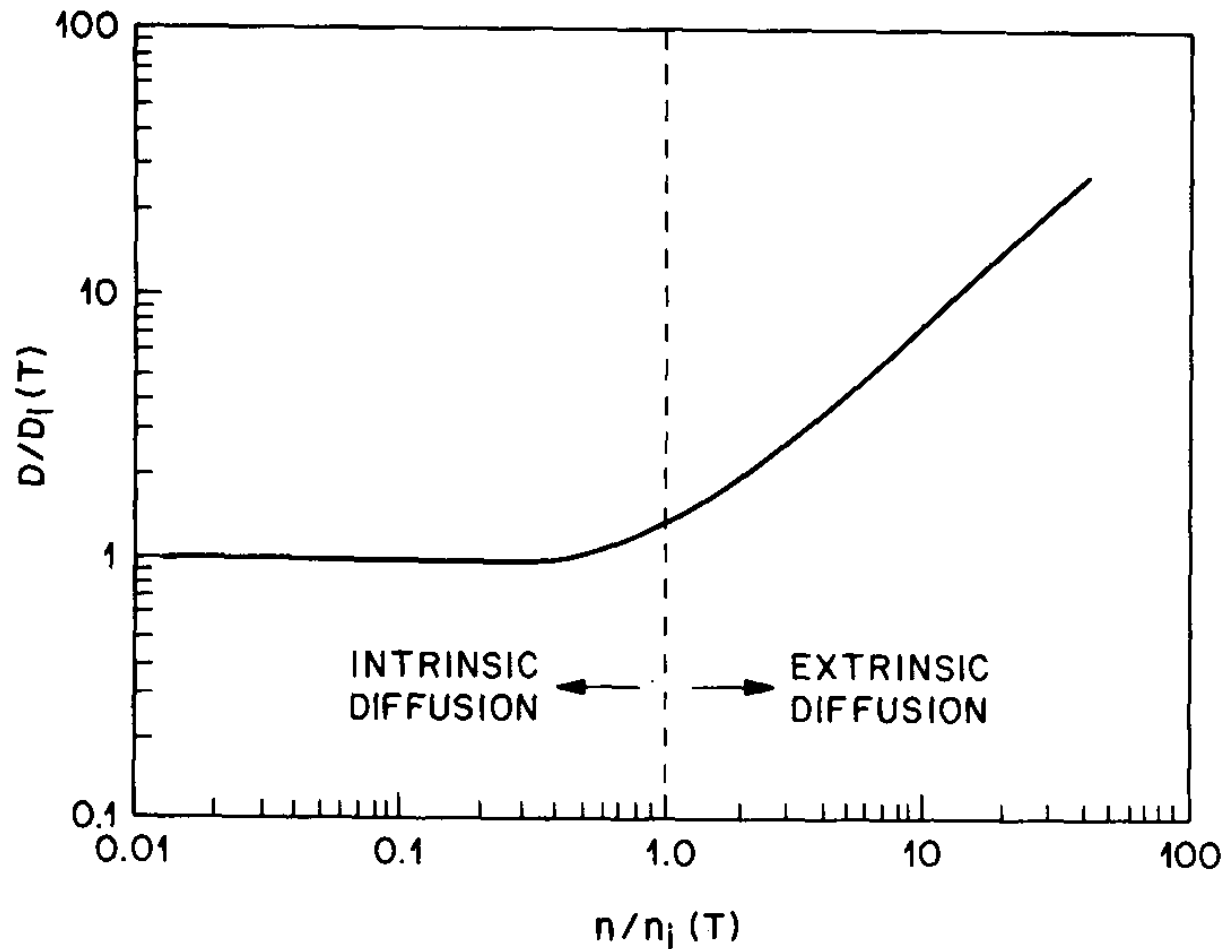
$$C(\infty, t) = 0$$

Thin surface layer with
total impurity present
of Q_0 [atoms/cm²]

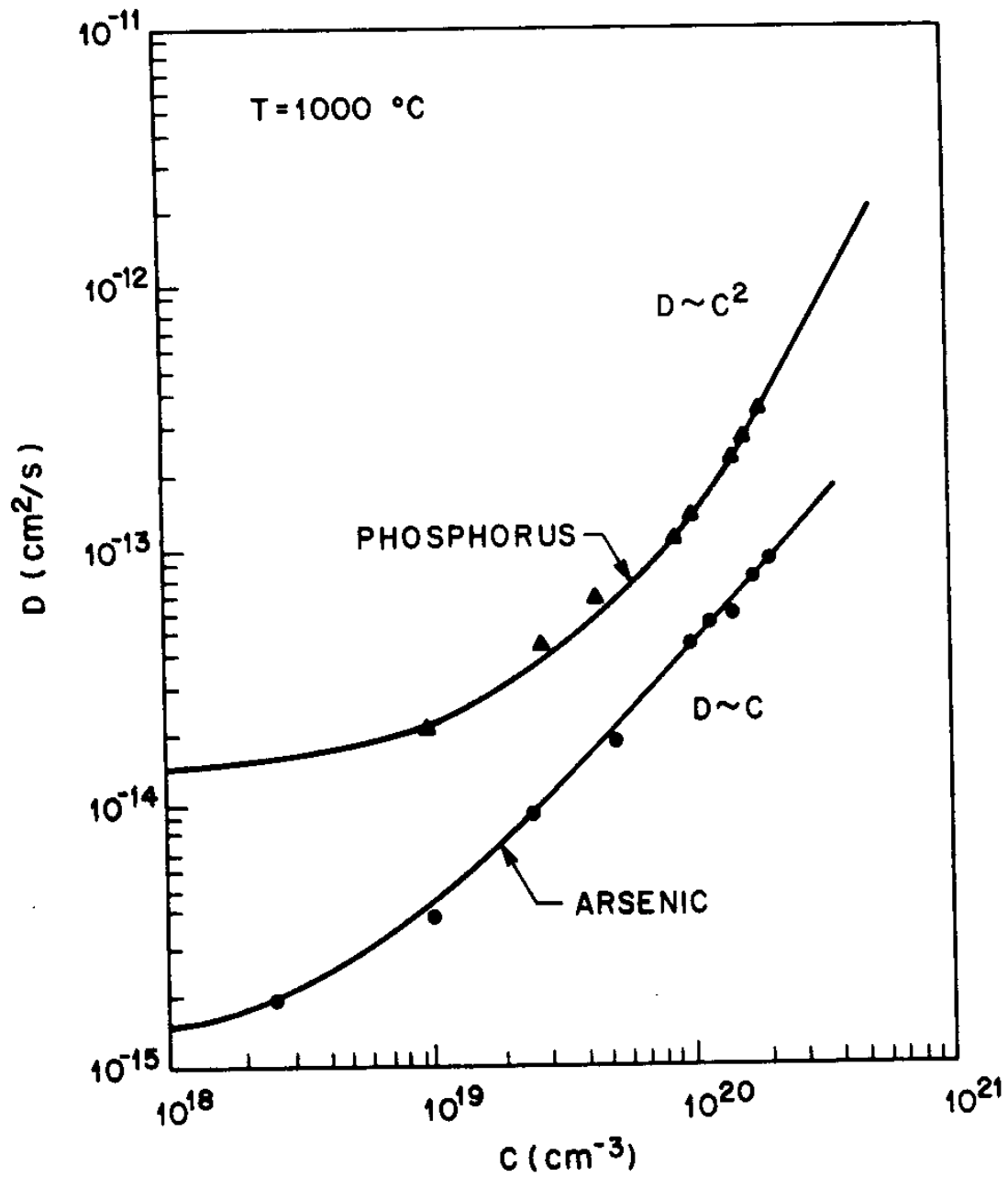


Solution:

$$C(x,t) = \frac{Q_0}{\sqrt{\pi Dt}} e^{\left[-x^2/4Dt\right]}$$



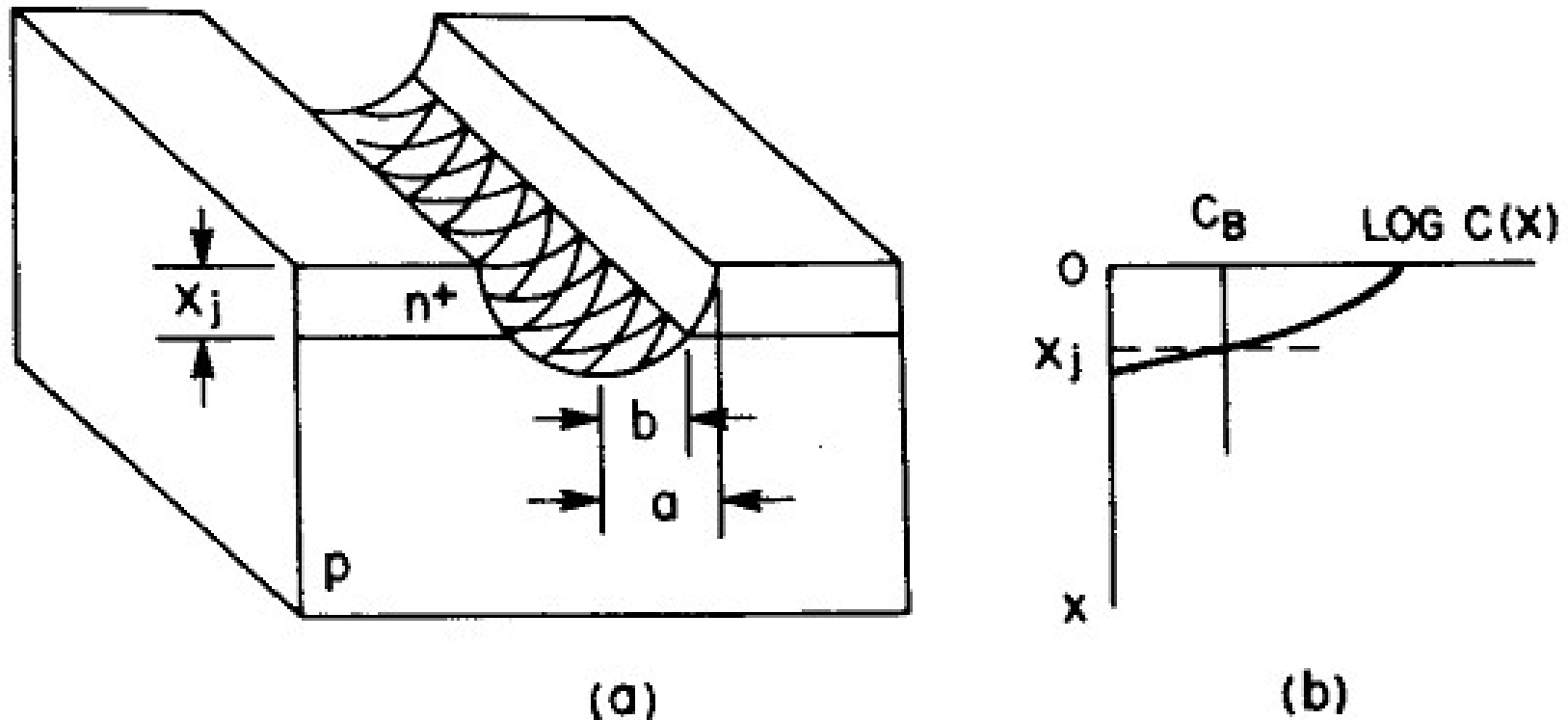
Donor impurity diffusion coefficient versus electron concentration showing regions of intrinsic and extrinsic diffusion.



Extrinsic diffusivities of arsenic and phosphorus in silicon as a function of dopant concentration.

Método para medida do perfil de dopagem

Medida de Profundidade de Junção

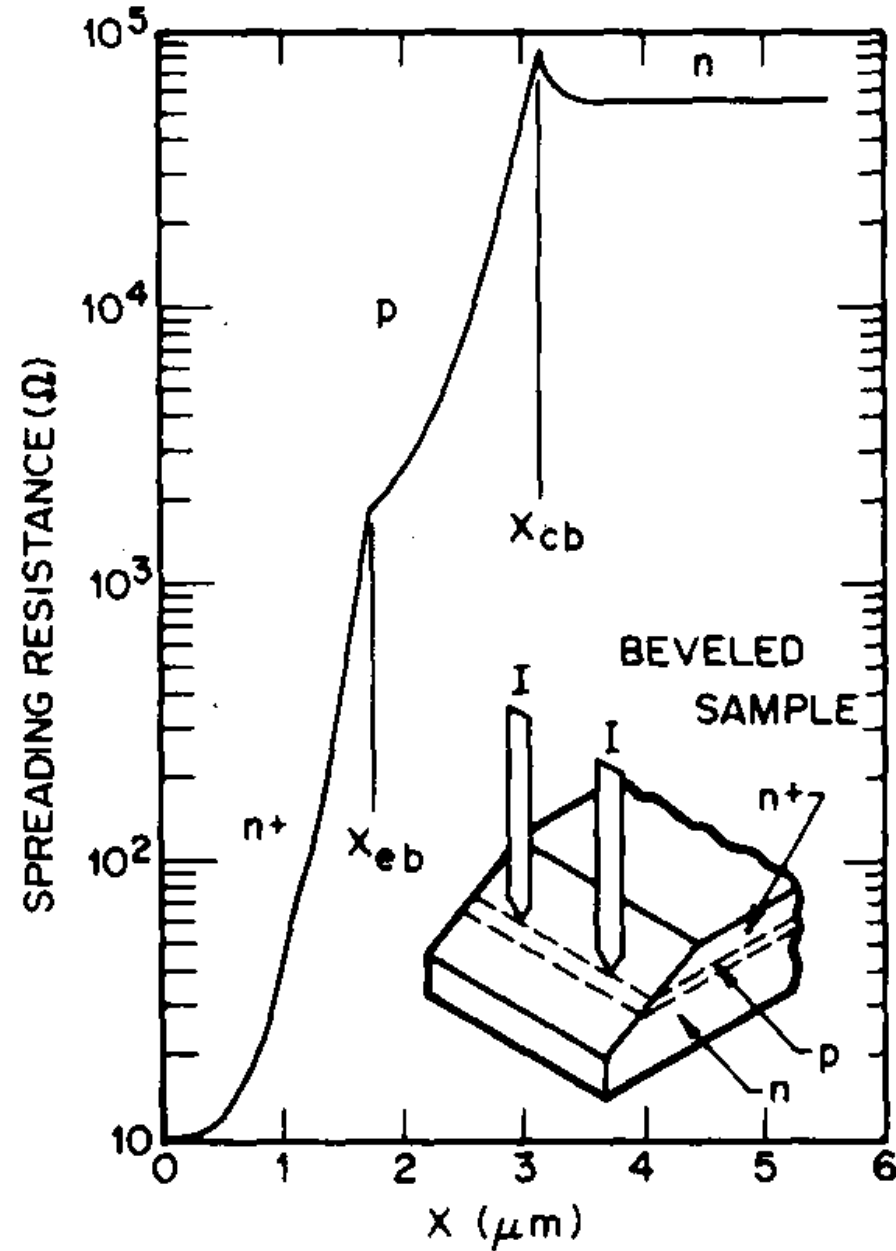


Junction depth measurement by grooving and staining.



Método para
medida do perfil
de dopagem

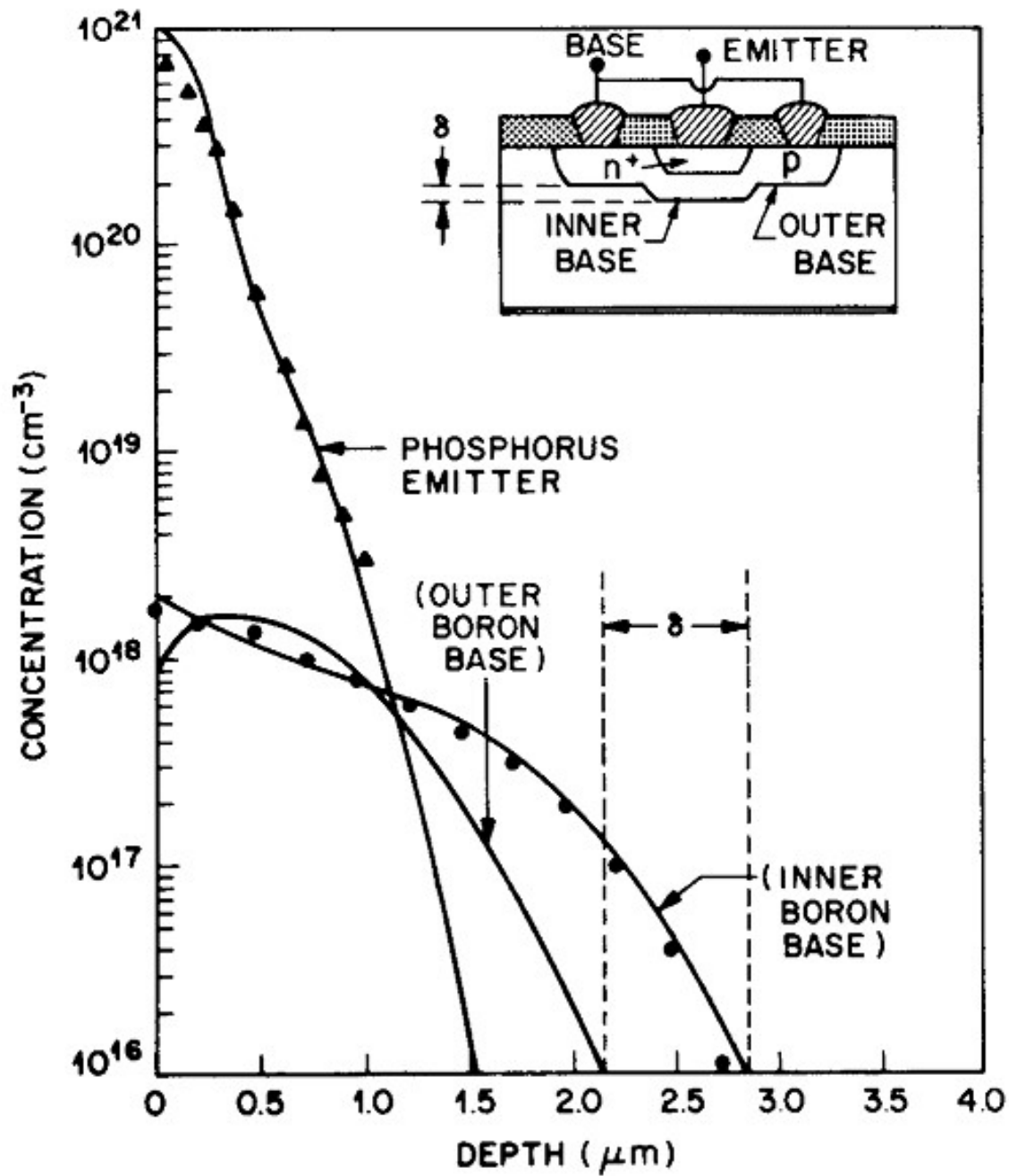
Spread Resistance Probe



The spreading resistance profile of an n-p-n transistor structure.

x_{eb} = the emitter-base junction

depth = 1.7 μm; x_{cb} = the collector-base junction depth = 3.2 μm.

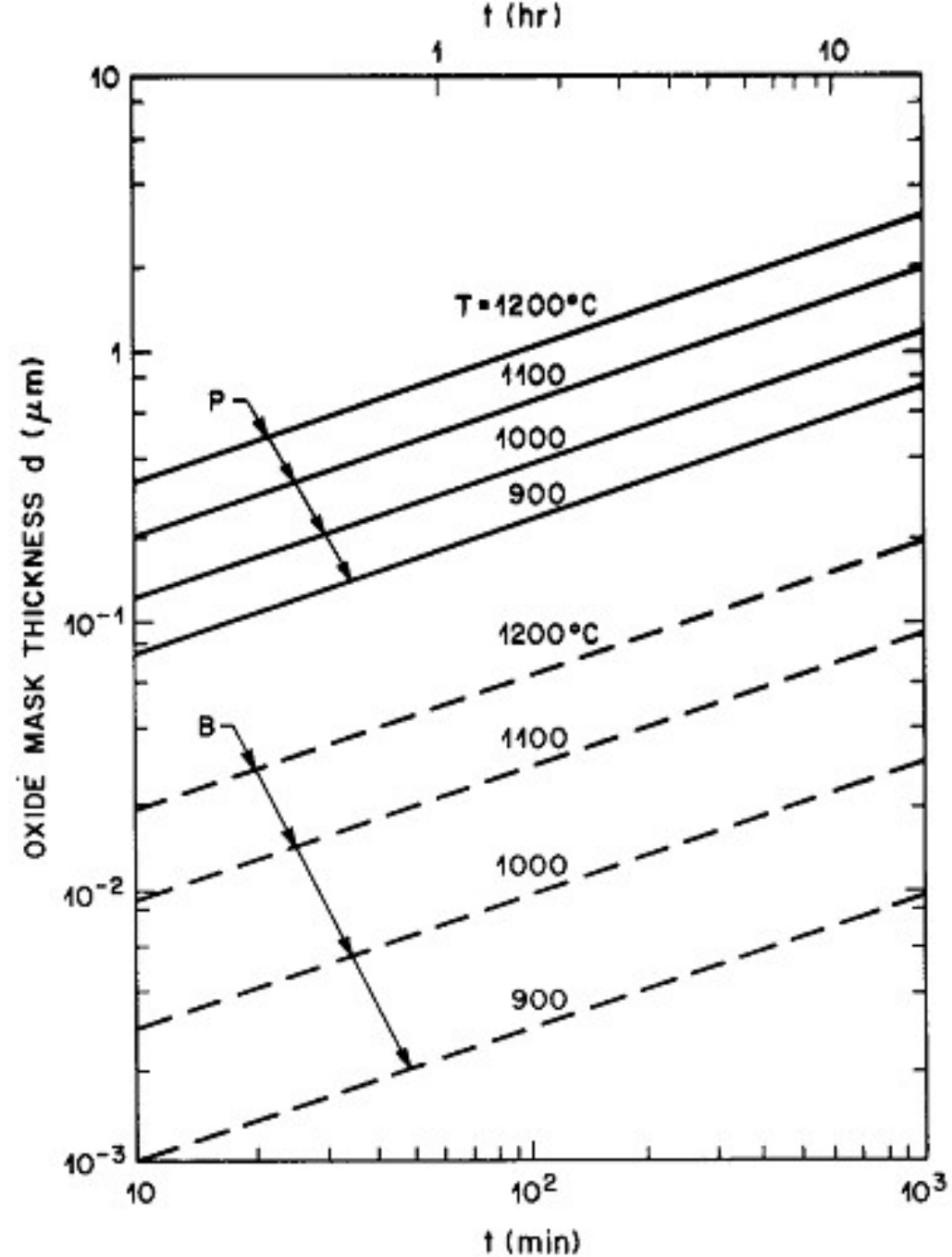


Calculated and measured boron and phosphorus n-p-n transistor profile showing the emitter push effect. Emitter diffusion is at 1000°C , for 1 hr, followed by a 900°C , 45-min steam oxidation.



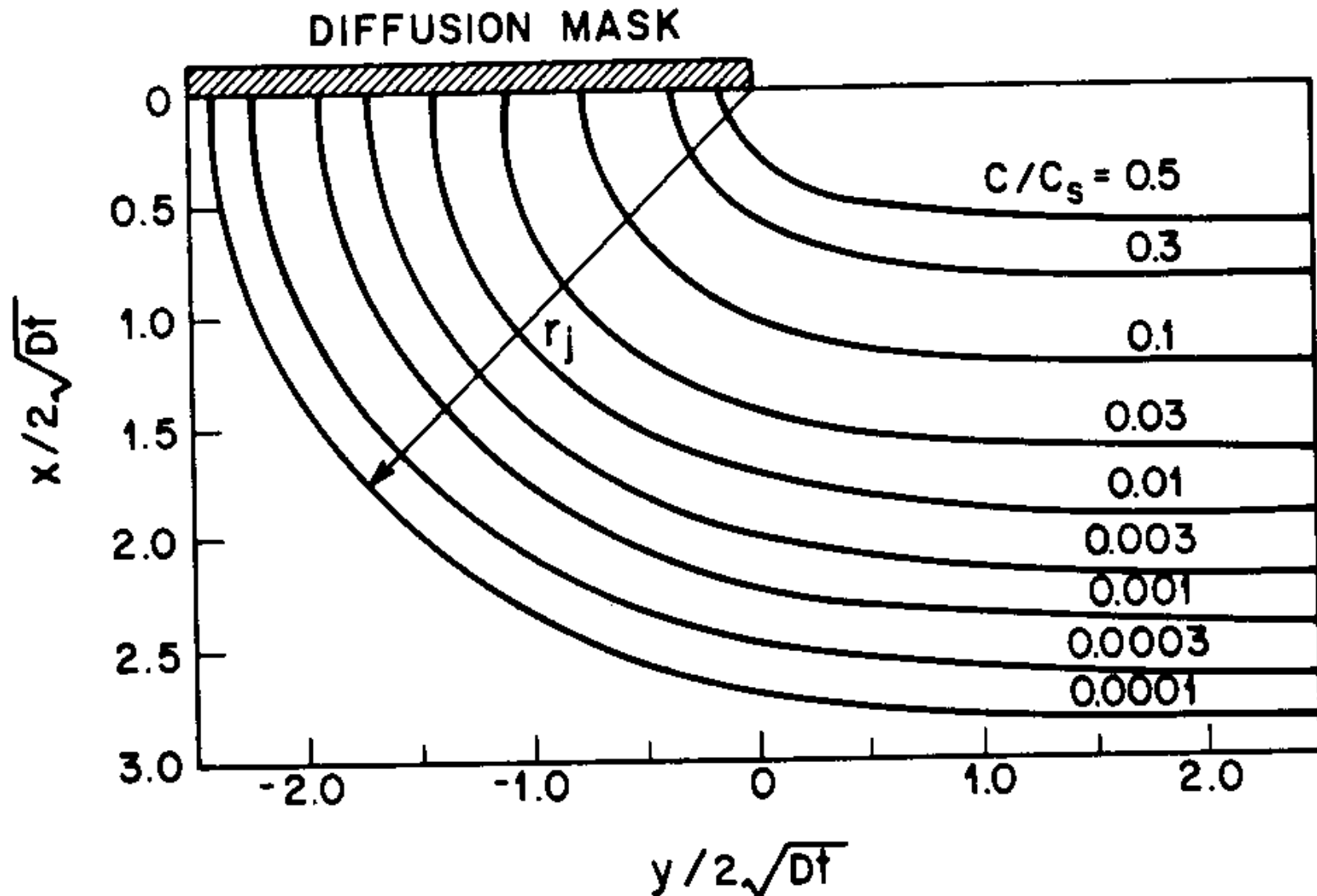
Óxido como Máscara

Este gráfico é utilizado para identificar a espessura mínima de SiO_2 necessária para ser utilizada como máscara numa Difusão Térmica



Minimum thickness of dry-oxygen-grown SiO_2 required to mask against phosphorus and boron as a function of diffusion time with diffusion temperature as a parameter.

Difusão Lateral



Diffusion contours at the edge of an oxide window, where r_j is the radius of curvature.

PSI-3552 Fabricação e Caracterização de Dispositivos Nanoeletrônicos

Dopagem por Implantação Iônica

Laboratório de
Microeletrônica
Escola Politécnica
Universidade de São Paulo

Prof. Roberto K. Onmori sala C2-70 (tel. 3091-5251)

email: RKONMORI@LME.USP.BR

Prof. Fernando J. Fonseca sala C2-65 (tel. 3091-0730)

email: FERNANDO.EPUSP@GMAIL.COM

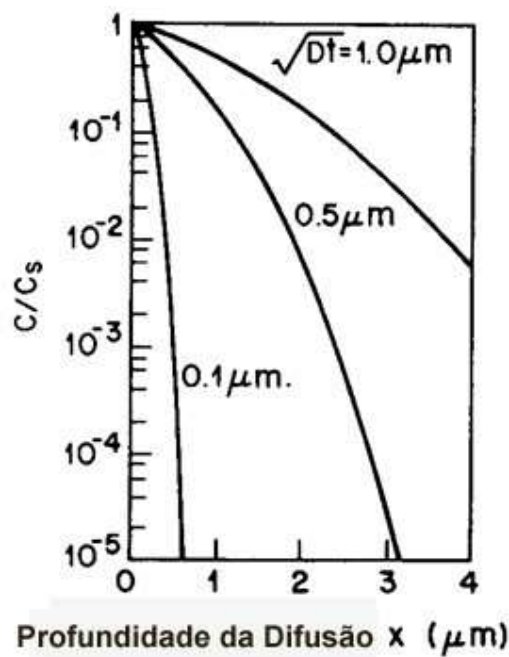


Problema a ser resolvido:

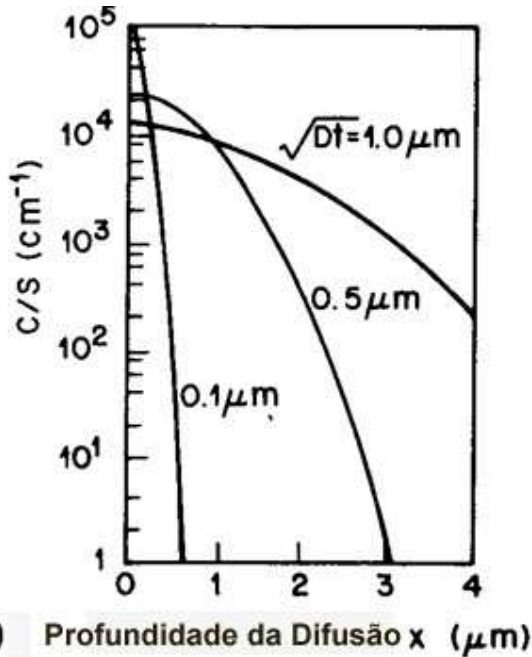
Conforme evolui uma tecnologia ...

As dimensões superficiais ficam menores e

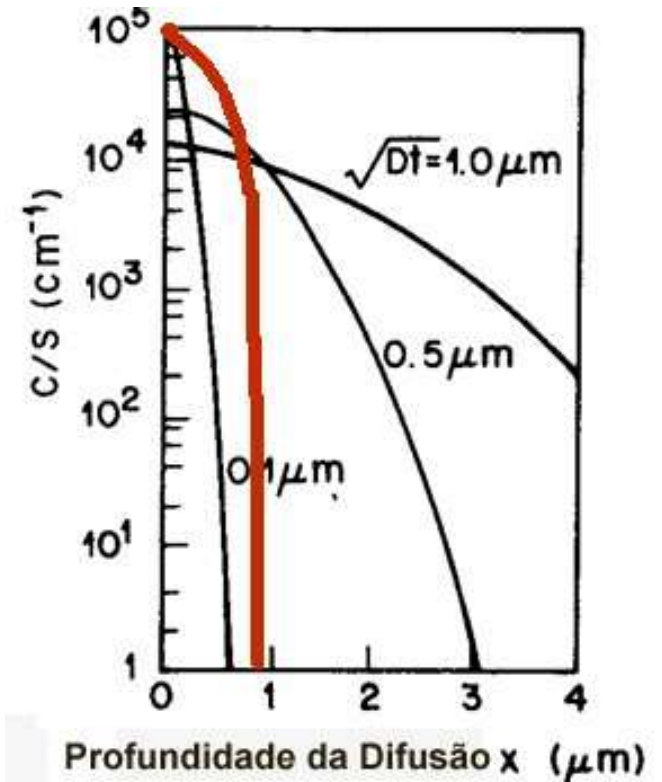
E as regiões dopadas devem ser cada vez mais dopadas e rasas;



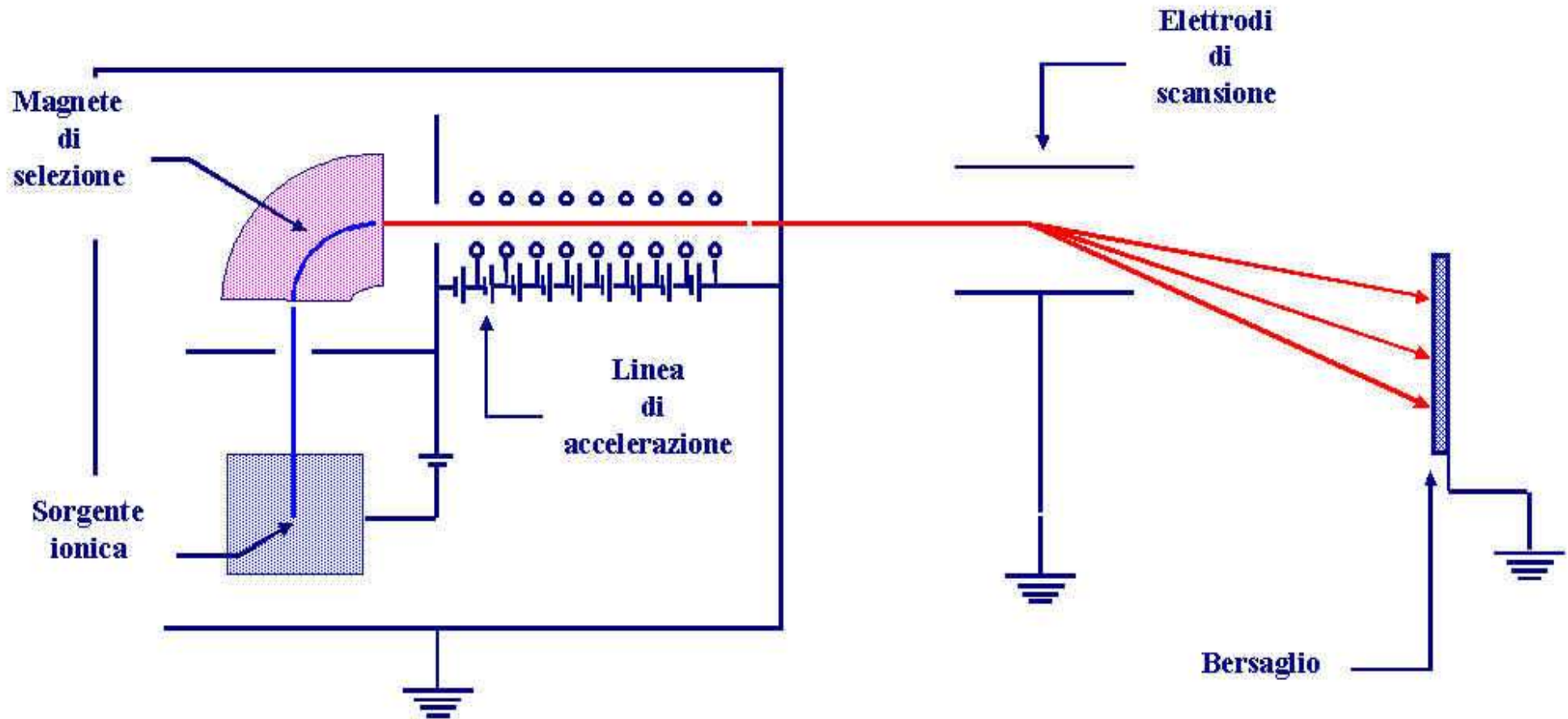
(a)



(b)

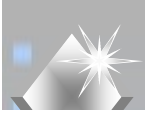


Implantação Iônica



Dose depende do da **corrente iônica** e **tempo** de implantação

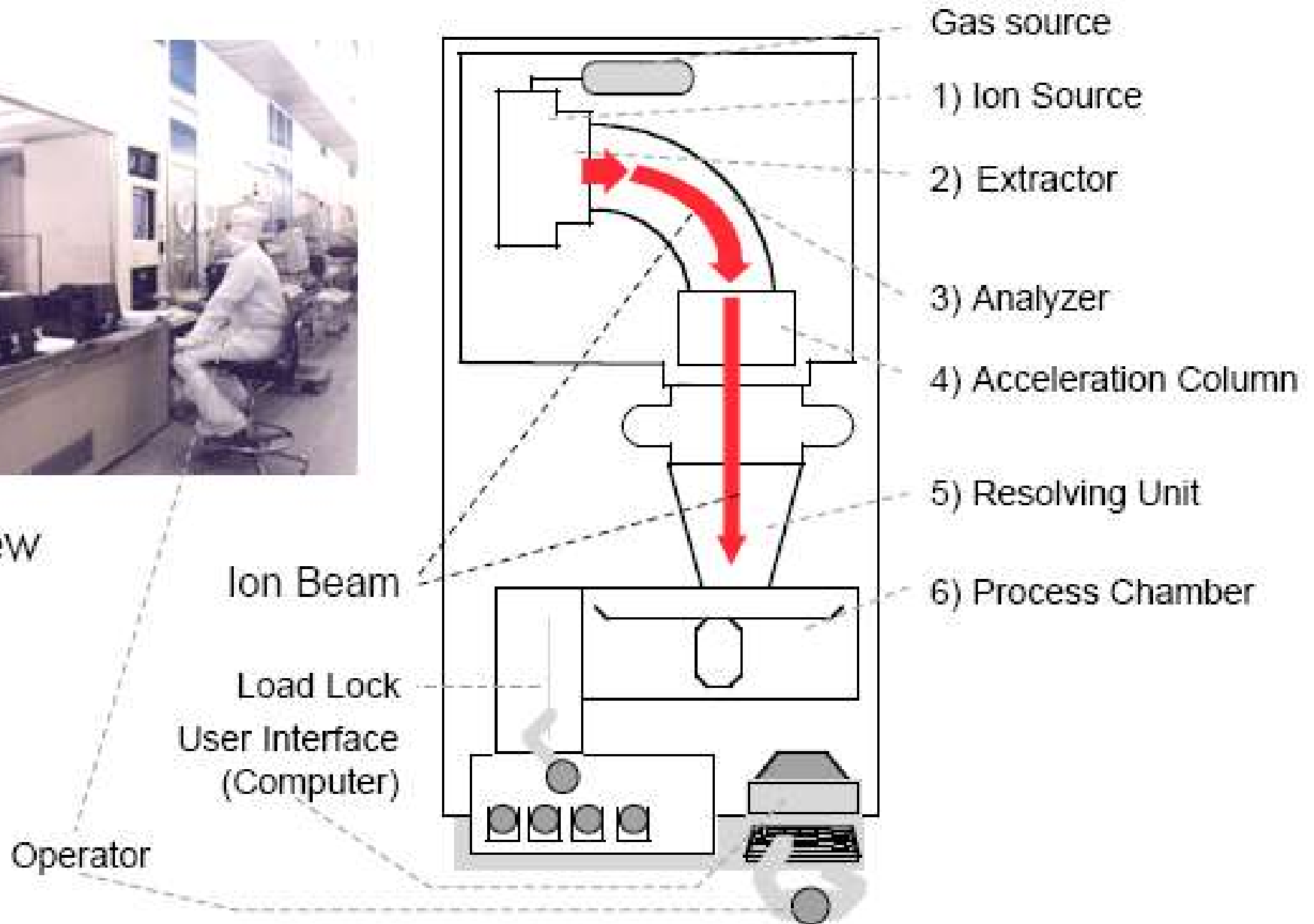
Profundidade depende da **energia** do íon



Equipamento de Implantação Iônica

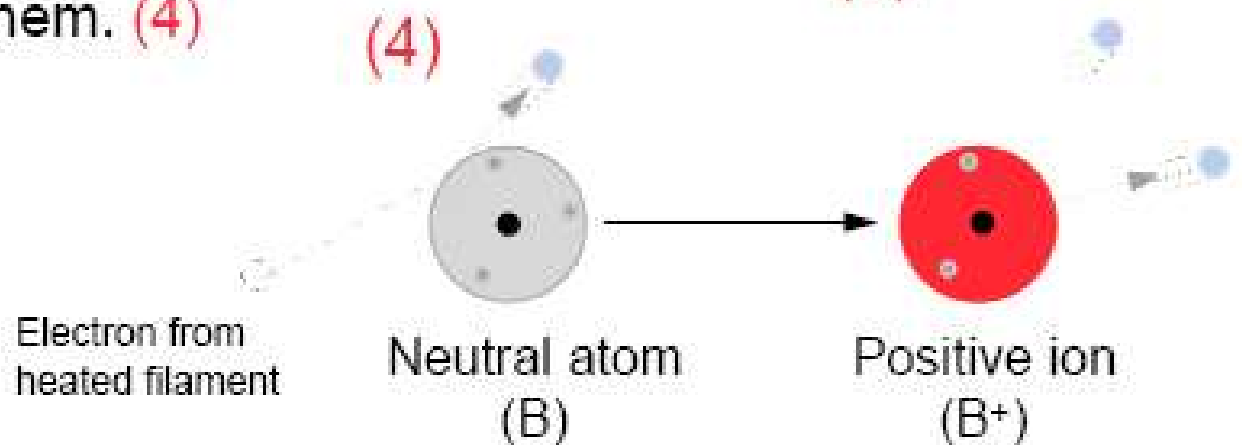
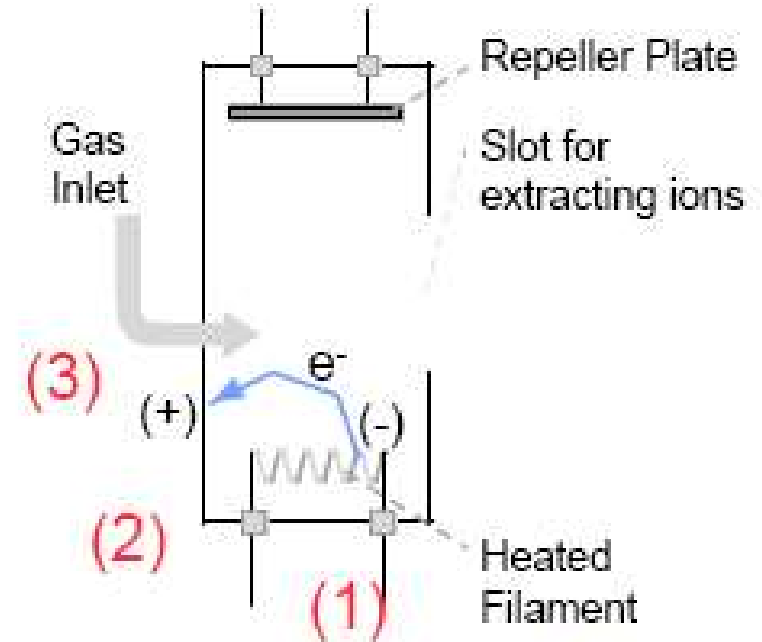
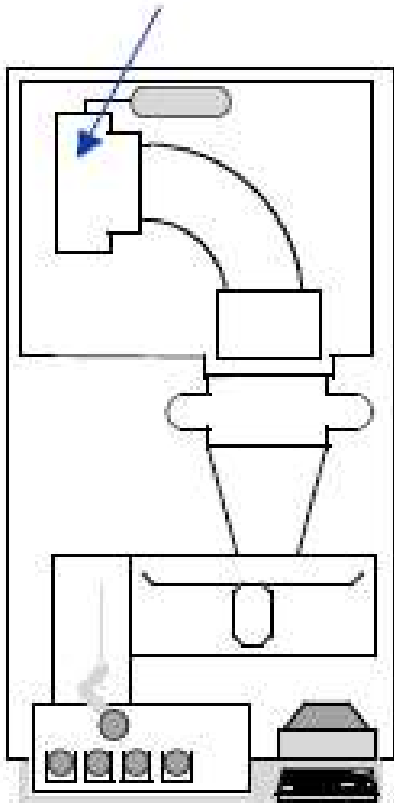


Outside view

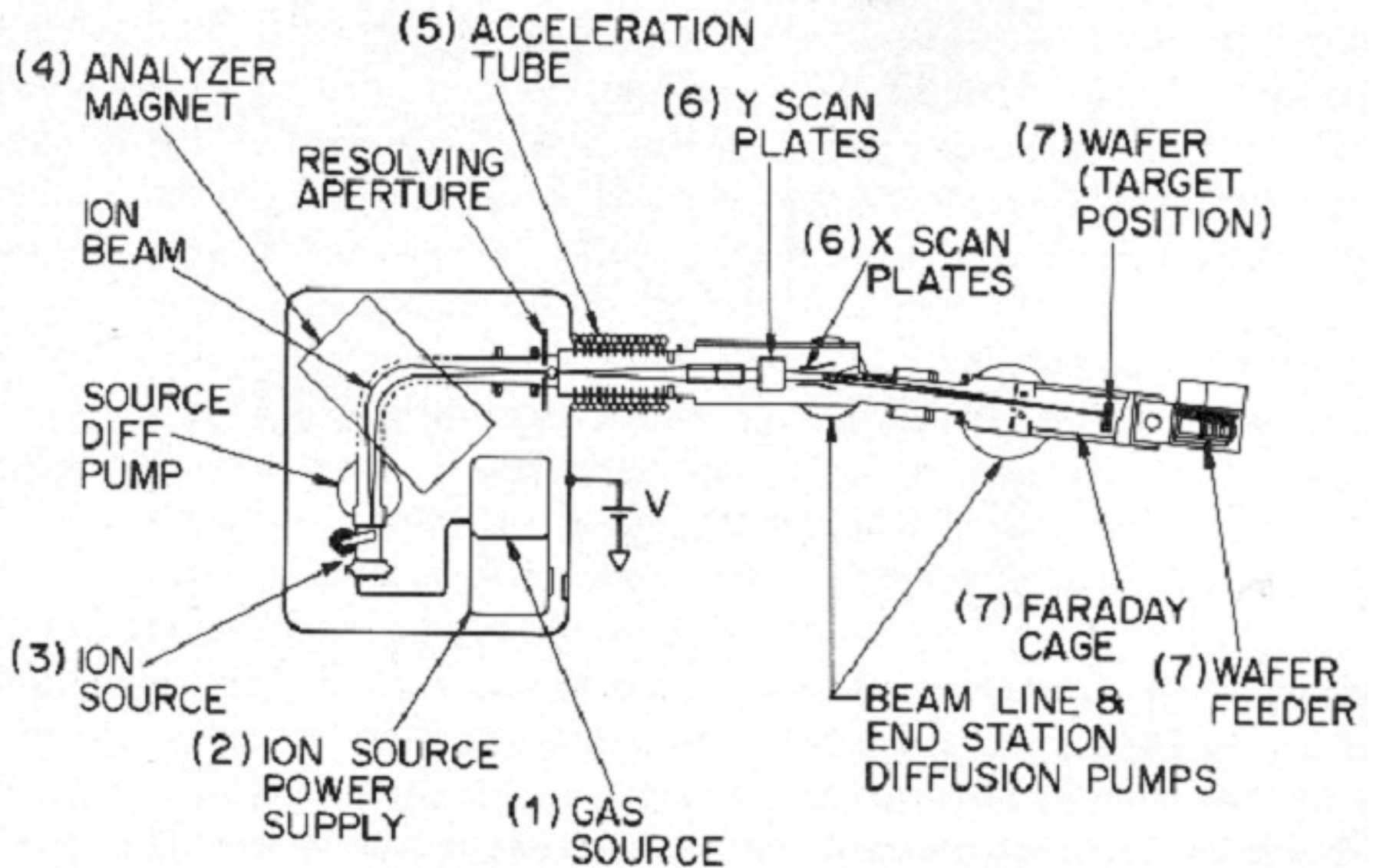


O Implantador Iônico

- The filament is heated. (1)
- Electrons are “boiled” off the heated filament. (2)
- The electrons are attracted to the positive wall. (3)
- On their way to the wall they hit neutrals and ionize them. (4)



Implantação Iônica



Schematic diagram of a typical commercial ion implant system.



Implantação Iônica

Como o Implantador seleciona o íon a ser implantado

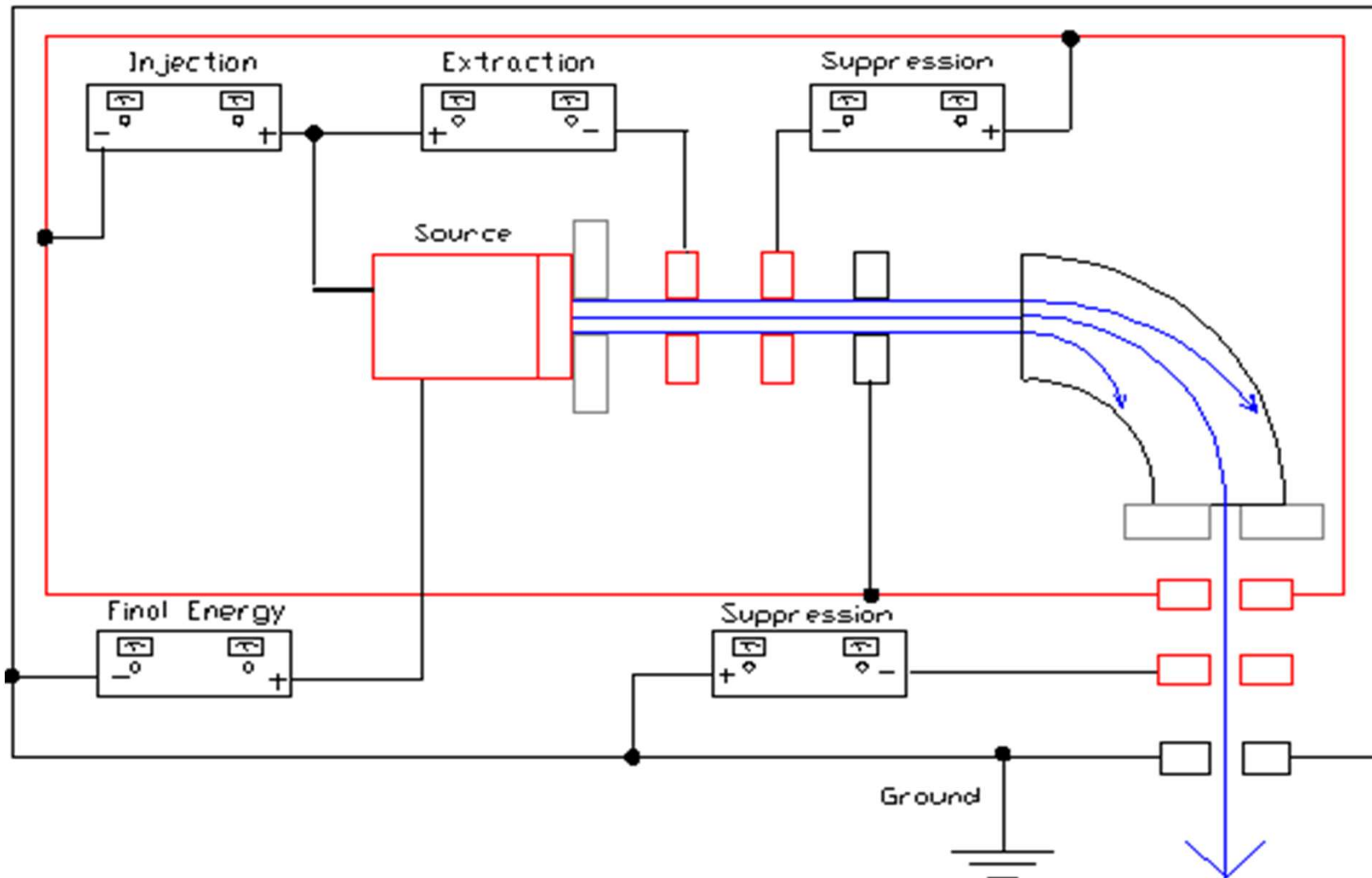


As ions enter the analyzer magnet,

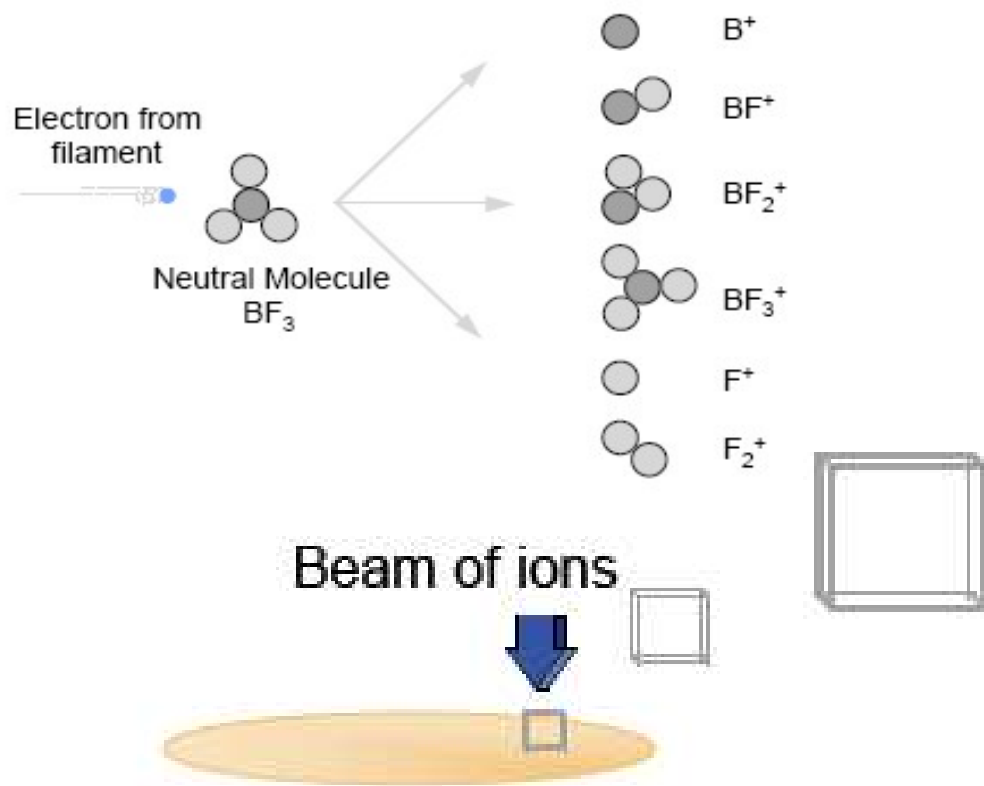


Implantação Iônica

Como o Implantador seleciona o íon a ser implantado



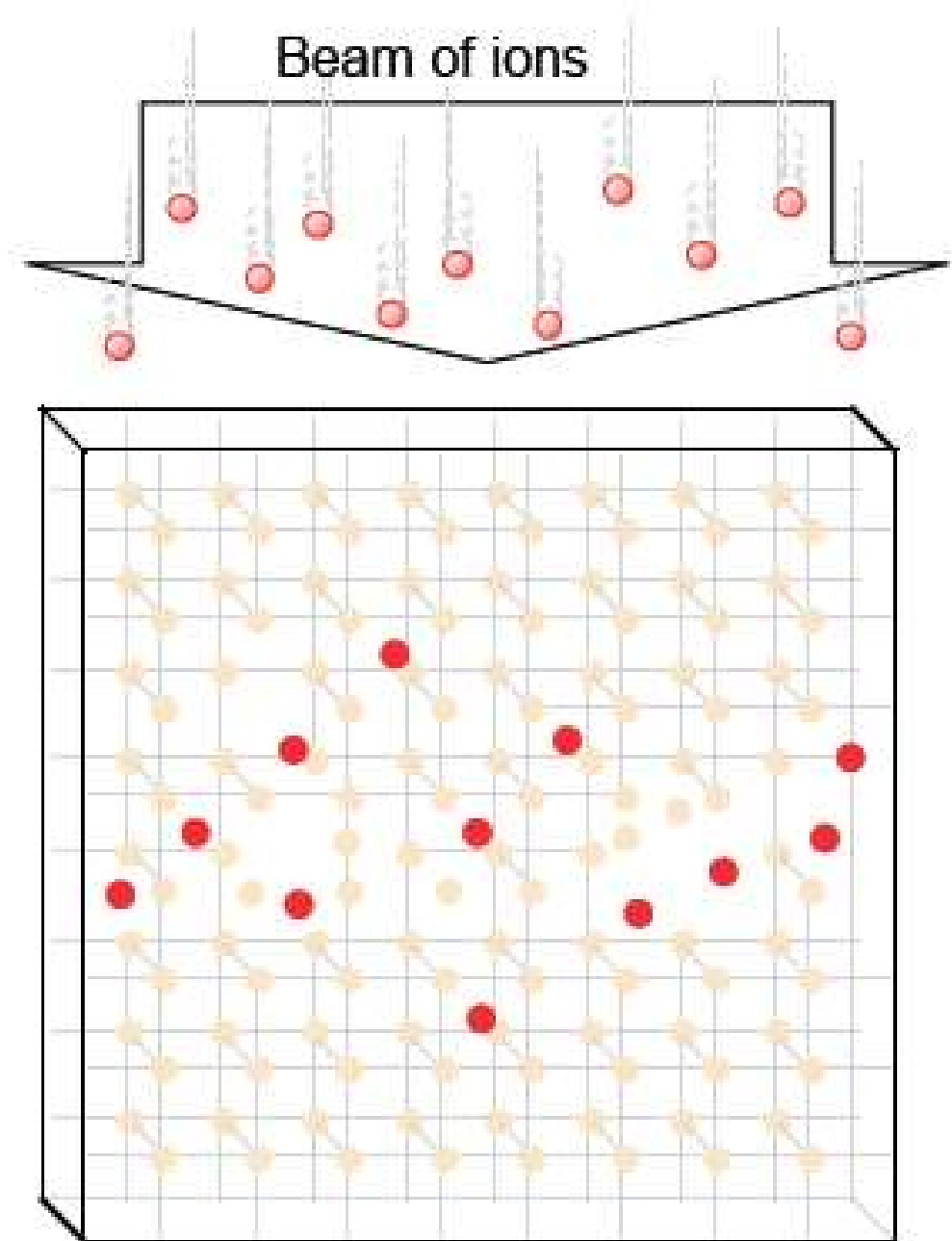
Some possible ions from BF_3 are shown here.

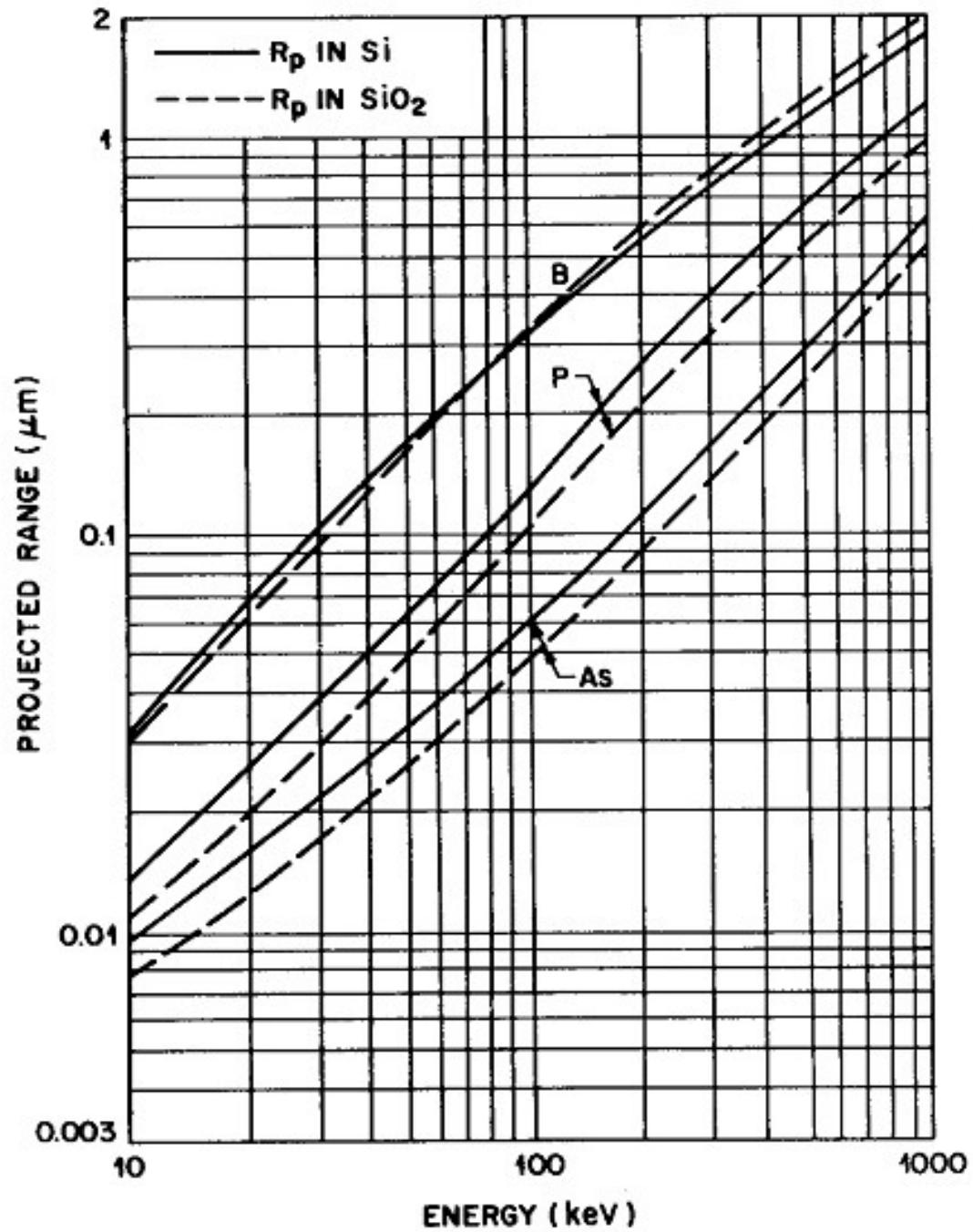


Beam of ions

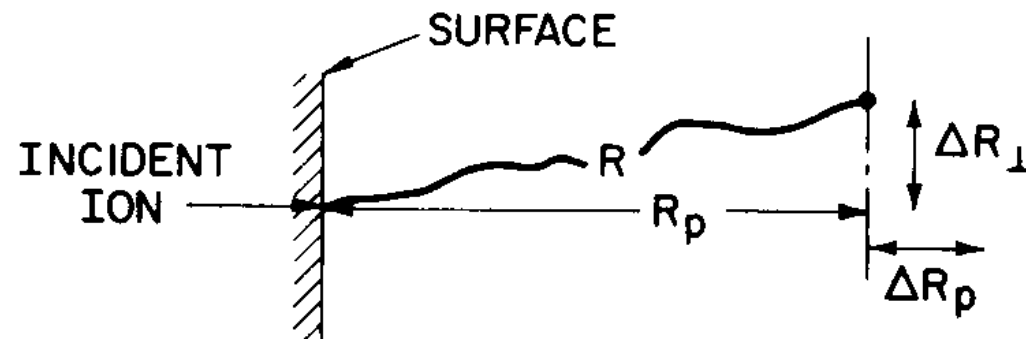
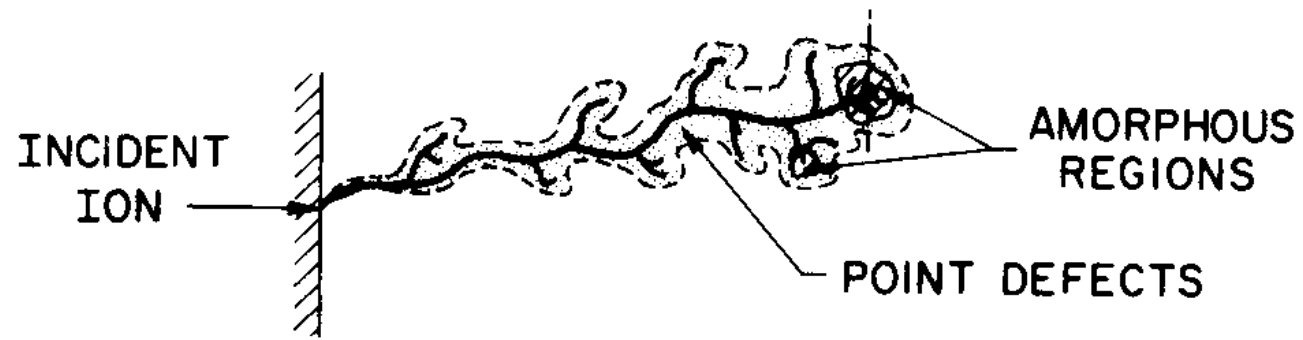
Si Wafer

- Silicon is doped with boron, phosphorous and arsenic by ion implantation
- Ions from the ion beam damage the lattice.





Projected range for B, P, and As in Si and SiO_2 at various energies.
The results pertain to amorphous silicon target and thermal SiO_2 .



$$n(x) = n(R_p) \exp \left[\frac{-(x - R_p)^2}{2\Delta R_p^2} \right]$$

Distribuição da dopagem por Implantação Iônica de Boro

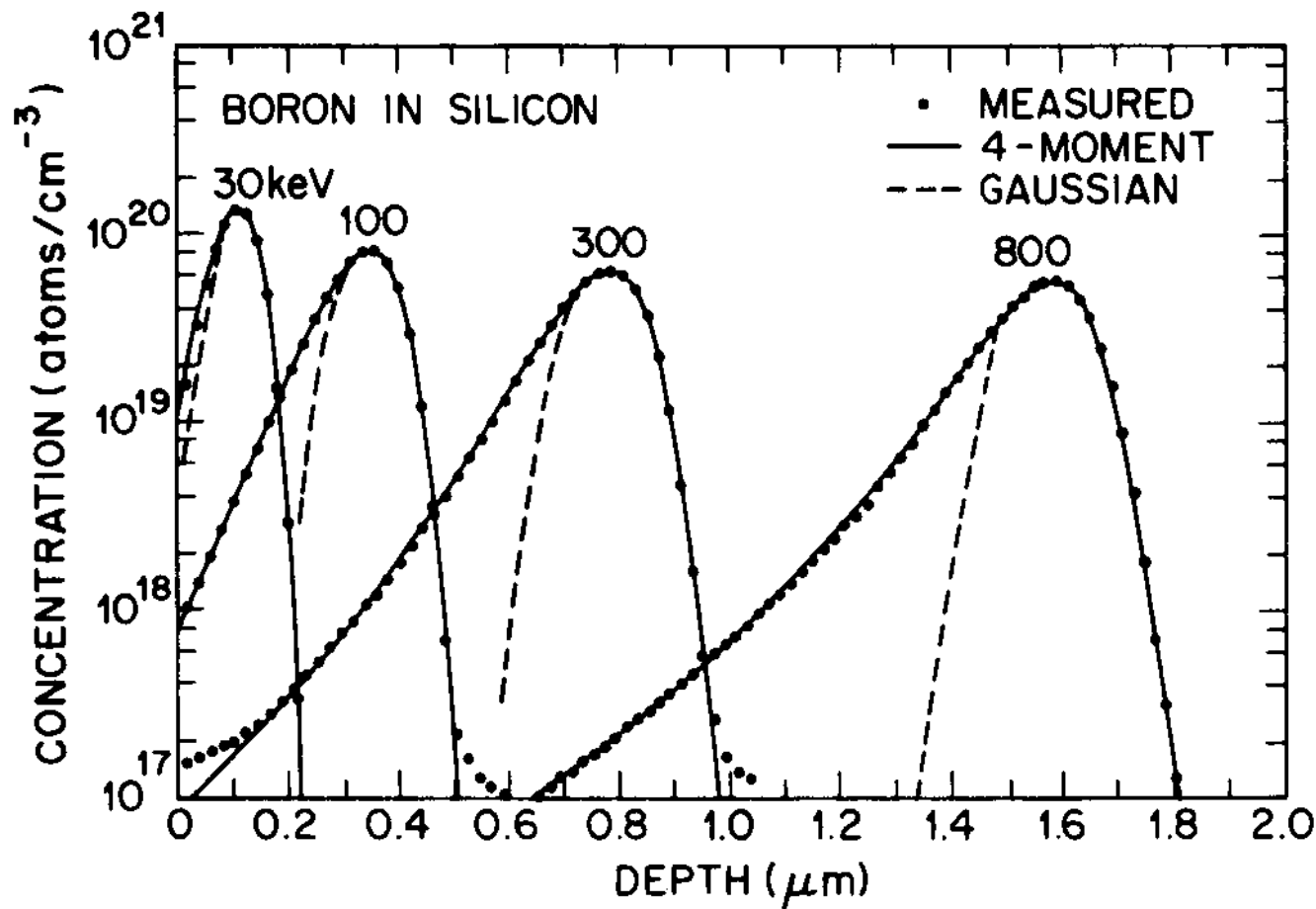


Fig. 5 Boron implanted atom distributions, with measured data points, and four-moment (Pearson-IV) and symmetric Gaussian curves. The boron was implanted into amorphous silicon without annealing. (After Hofker, Ref. 21.)

Danos na Estrutura Cristalina

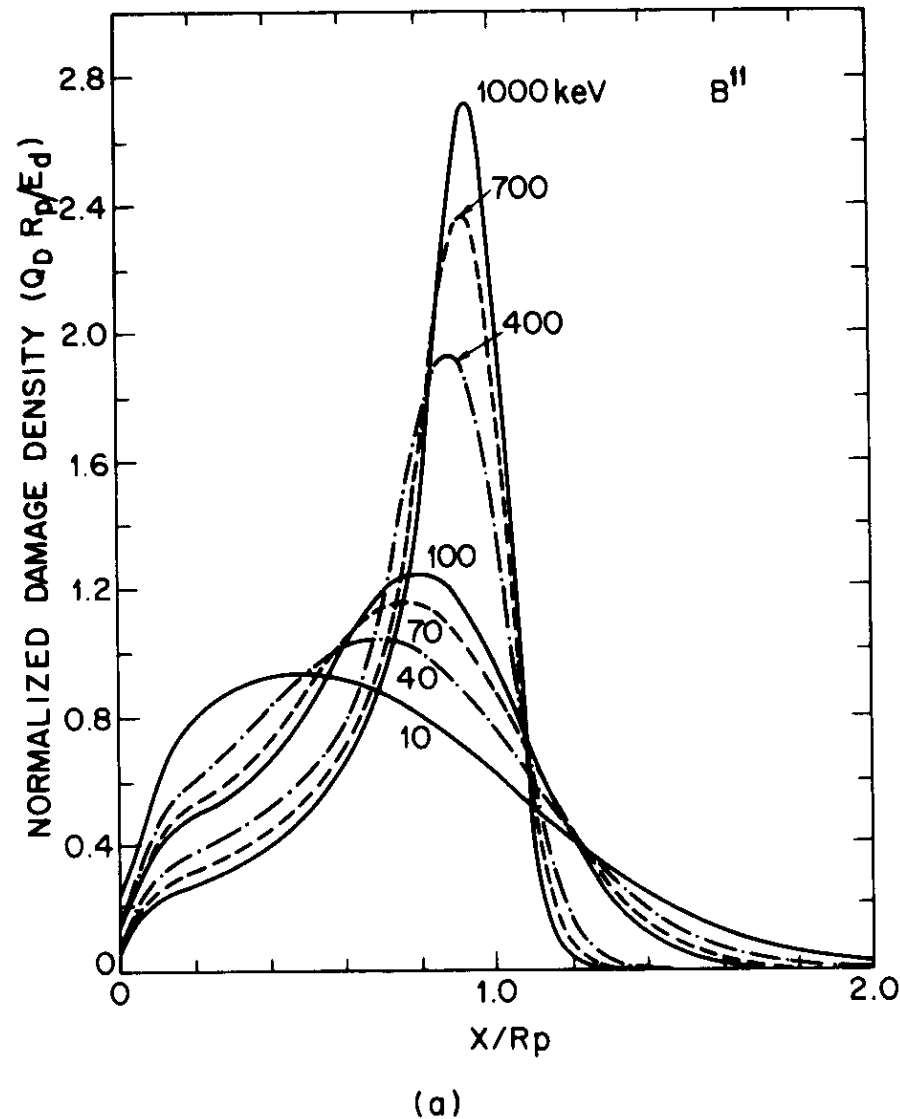
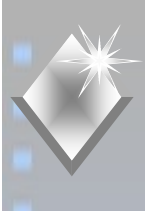


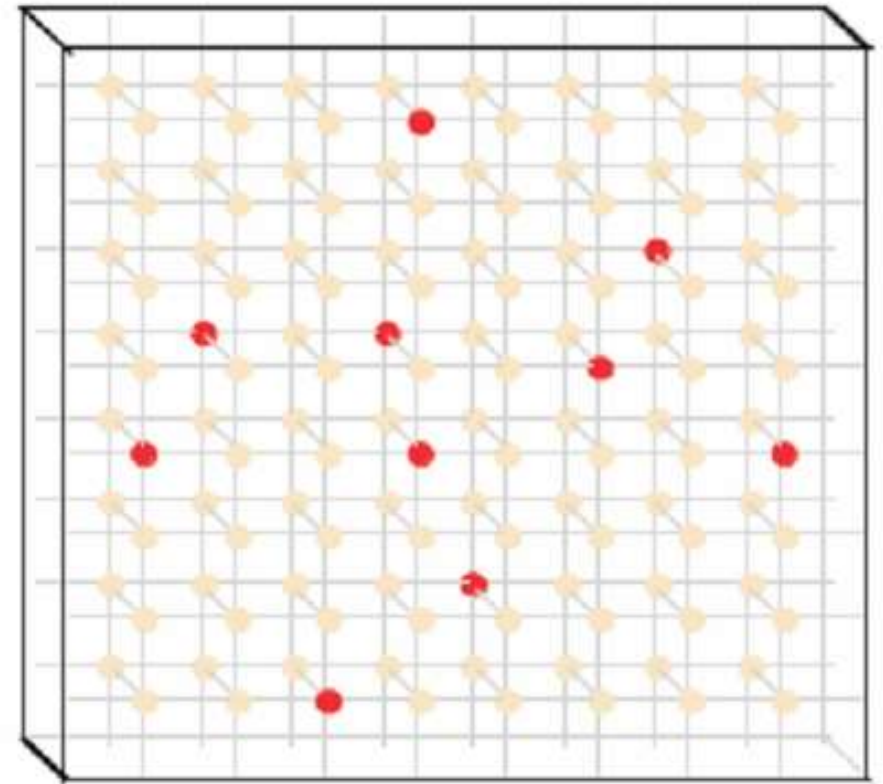
Fig. 12 Calculated damage density profiles of (a) boron and (b) arsenic. (After Brice, Ref. 30.) The values of deposited energy Q_D are obtained by multiplying the normalized damage density by E_d/R_p (eV/Å). Some values of E_d/R_p for B are 12.9 (10 keV) and 6.1 (100 keV); for As they are 91.4 (10 keV) and 99.3 (100 keV).



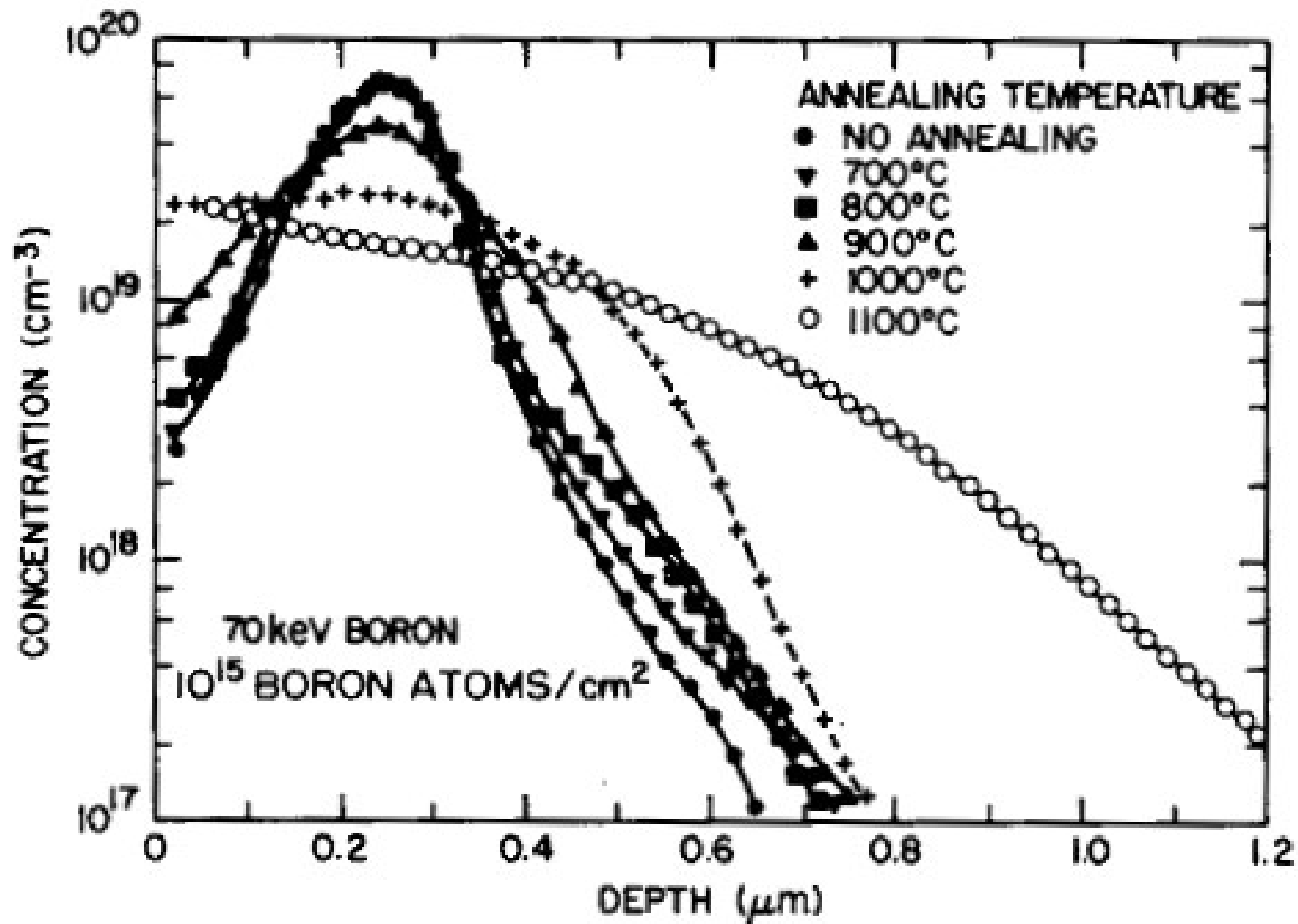
Recozimento Térmico (*Annealing*)



- Annealing is a process where the wafer is heated to repair the damage to the lattice
- The dopant ions become part of the crystal lattice (Activation)
- The ions also spread out during anneal (Diffusion)

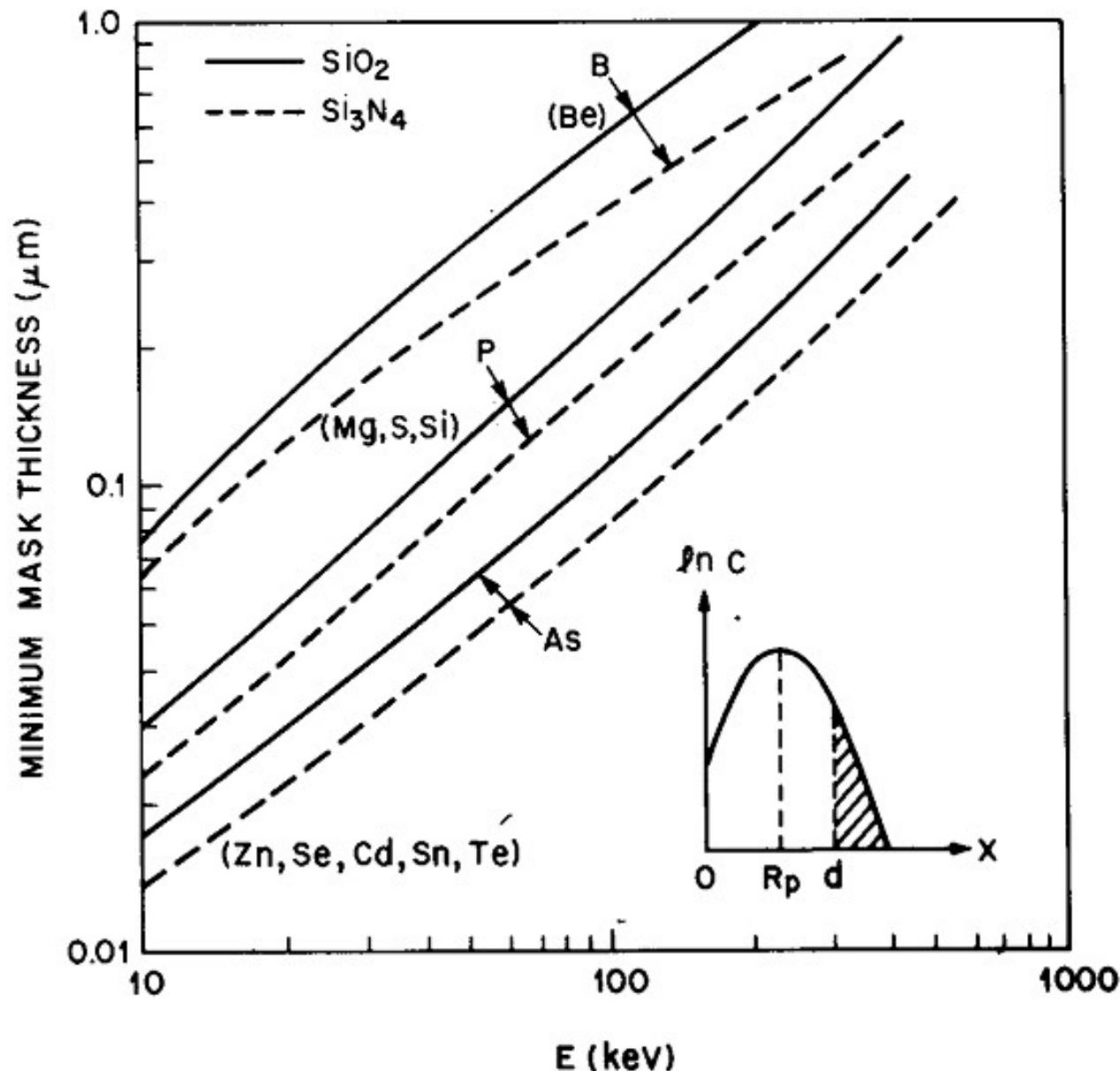


Recozimento Térmico (*Annealing*)



Boron atom concentrations as a function of annealing at various temperatures.
The anneal time is 35 minutes. (After Hofker, Ref. 21.)

Proteção da dopagem por Implantação Iônica



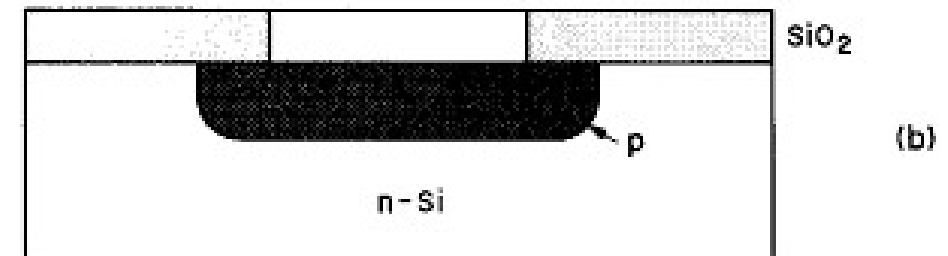
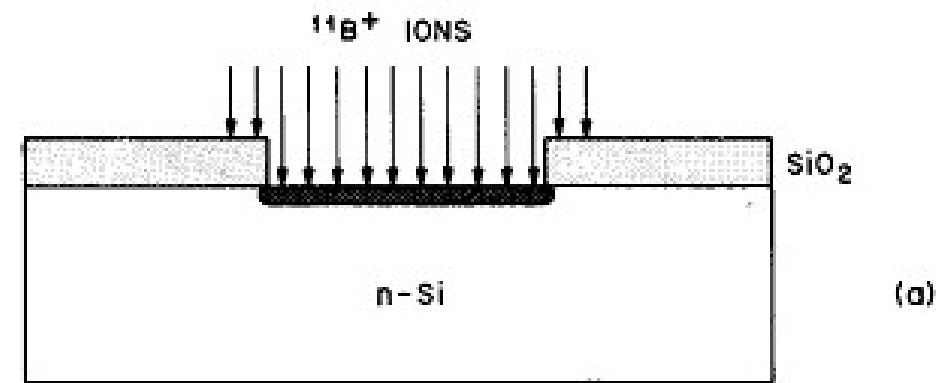
Espessura de SiO₂ e Si₃N₄ para proteção da dopagem por Implantação Iônica

Minimum thickness of SiO₂ and Si₃N₄ for a masking effectiveness of 99.99%.
Insert shows ion penetration beyond a depth d .

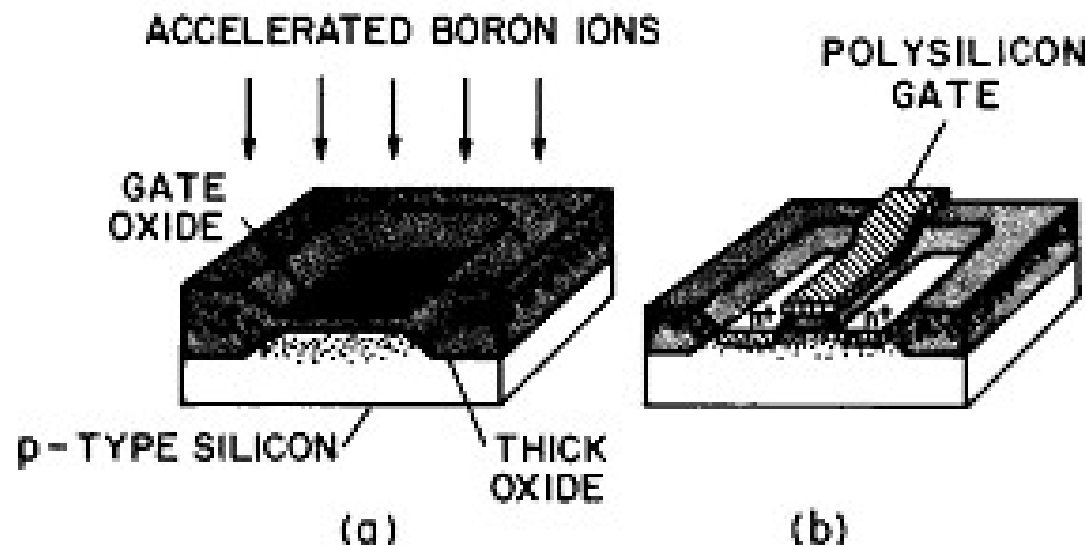


Usos

- Ajuste na tensão limiar V_{th} de um transistor MOS
- Dopagem nos contatos de Gate de um MOSFET



(a) Predeposition using ion implantation. (b) After drive-in diffusion.



Threshold voltage adjustment using boron ion implantation.²⁹

Parâmetros de Implantação

Equipamento:

Tempo
Corrente

Energia

Ângulo de incidência
Na lâmina

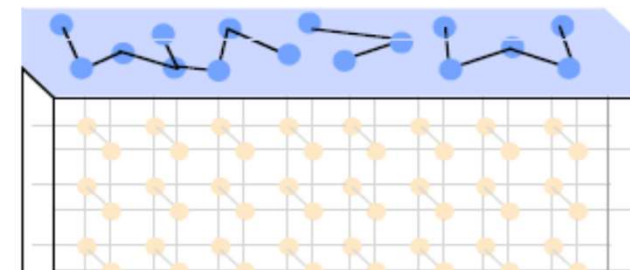
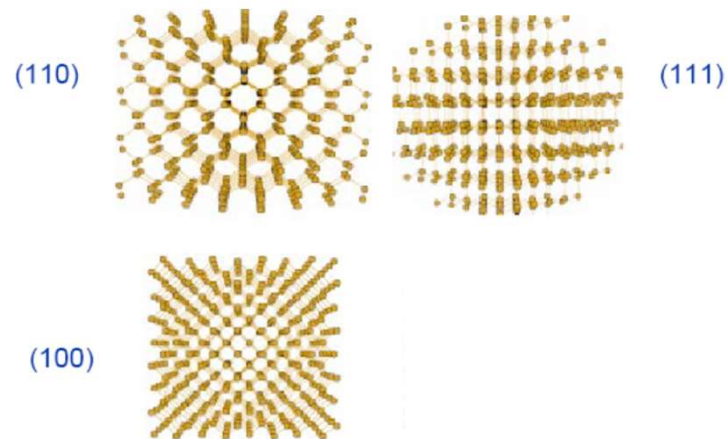
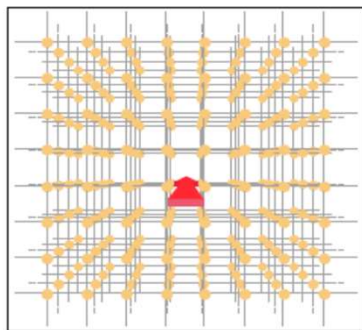
Resultado:

Dose

Profundidade

Uniformidade

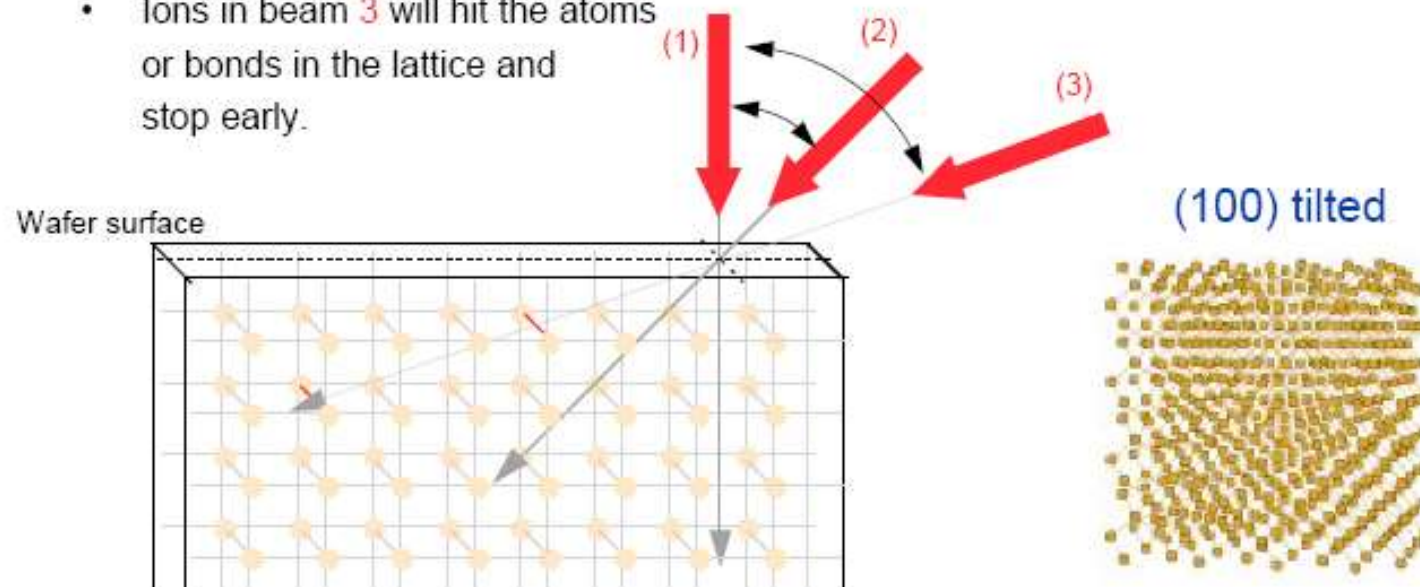
Canalização (*Channeling*)



Cargas no processo de Implantação

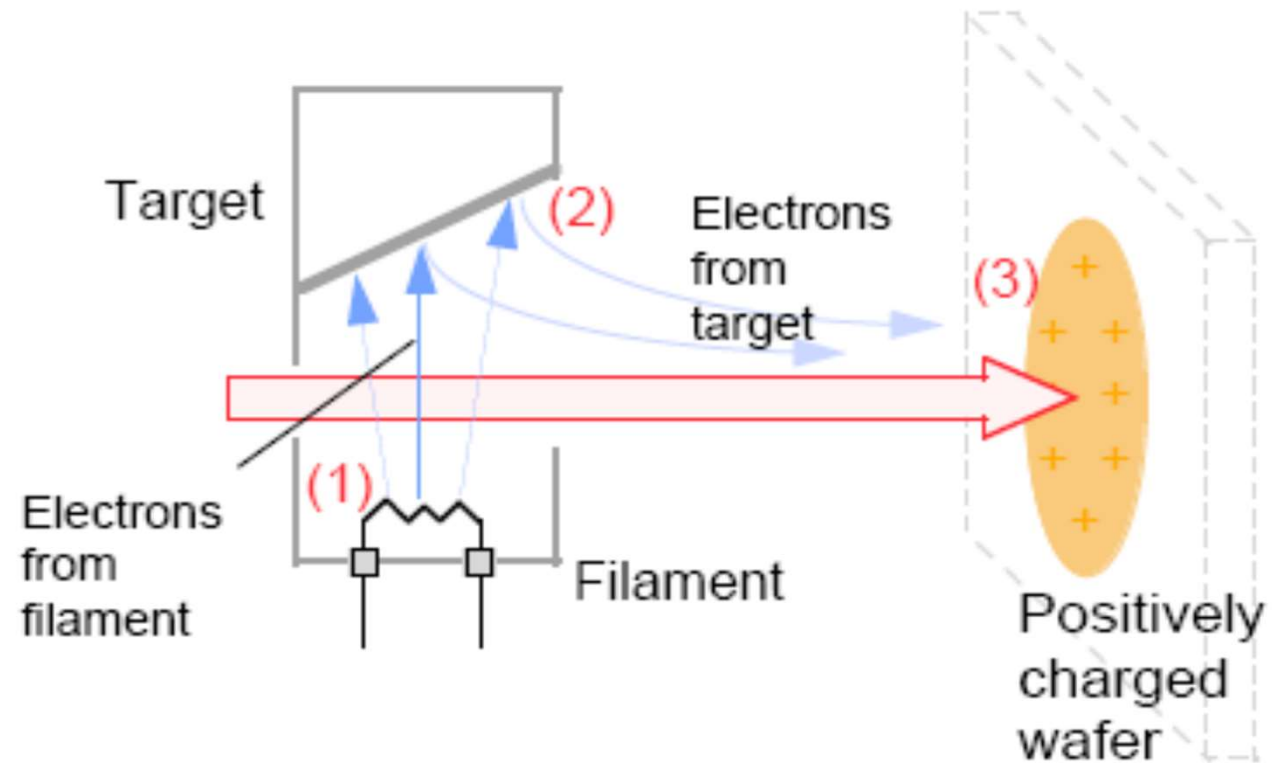
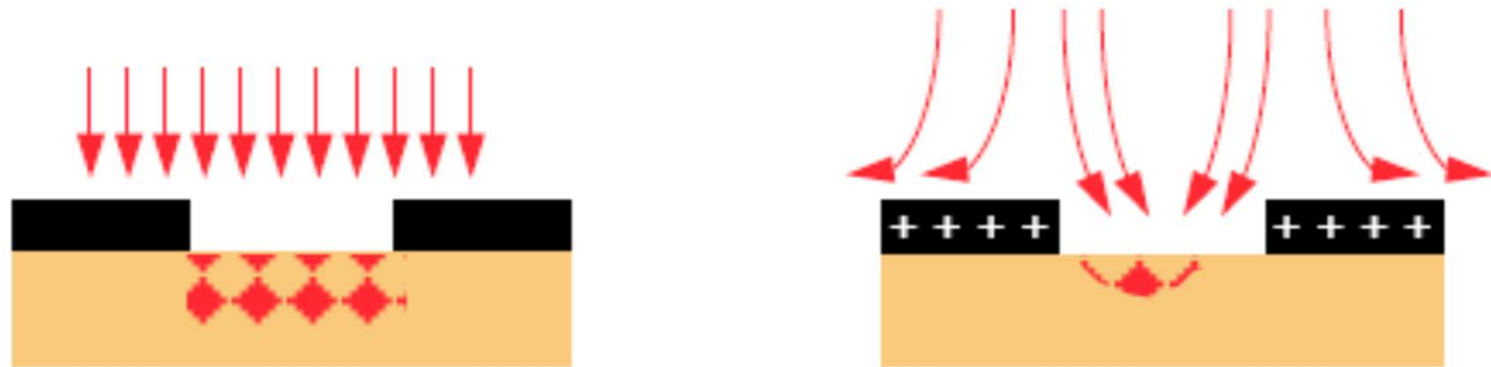


- Ions in beam 3 will hit the atoms or bonds in the lattice and stop early.



Com inclinação da lâmina entre 3° e 5°

Cargas no processo de Implantação



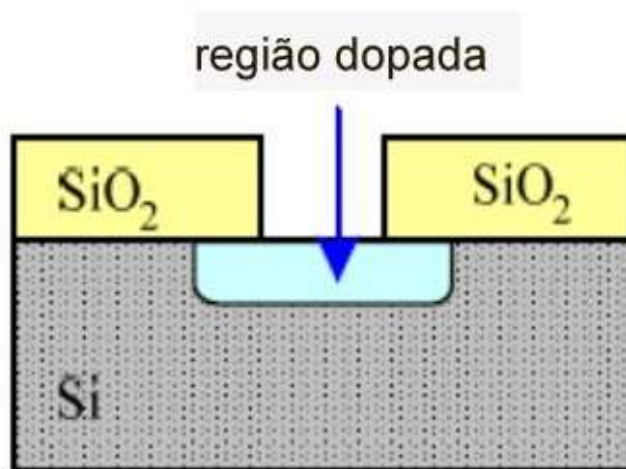
Comparação

Difusão Térmica

Alta Temperatura,
Máscara densa (SiO_2)

Perfil de dopagem ISOtrópico

NÃO consegue controlar
INDEPENDENTEMENTE
a concentração e a
profundidade da junção

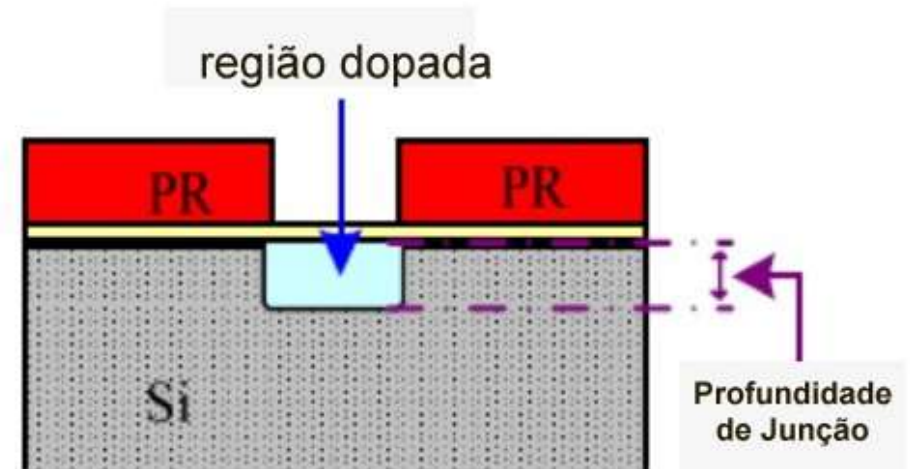


Implantação Iônica

Baixa Temperatura,
Máscara de Fotoresiste (FR)

Perfil de dopagem ANISOtrópico

CONSEGUE controlar
INDEPENDENTEMENTE
a concentração e a
profundidade da junção



Contaminantes

- Podem vir de:
- • Metálicos – impactos nas paredes....
 - Fe, Cr, Ni.
- • resíduos – várias espécies de dopantes (P, As, B...)
- • Na, Ca, Mg,
- • Óleo da Bomba difusora, carbono, oxigênio, nitrogênio...