PSI-3552 Fabricação e Caracterização de Dispositivos Nanoeletrônicos

Aula 03 - Dopagem
Difusão Térmica

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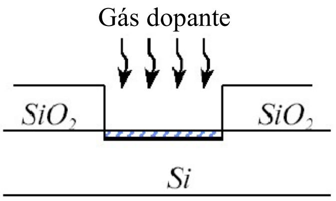
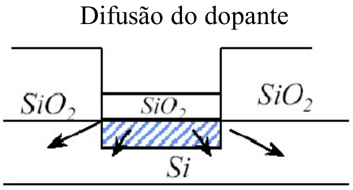
Introdução

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

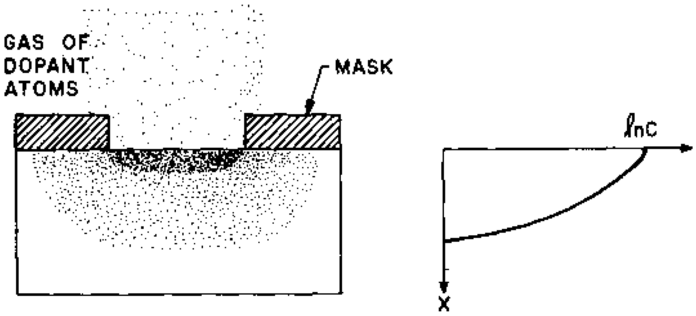


- Dopagem é a exposição da lâmina de Si em uma fonte contendo P, As ou B (deposição) e

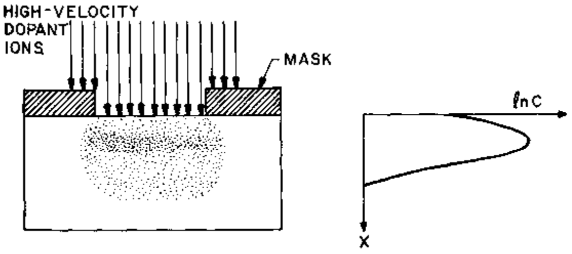


- e a sua difusão em alta temperatura

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

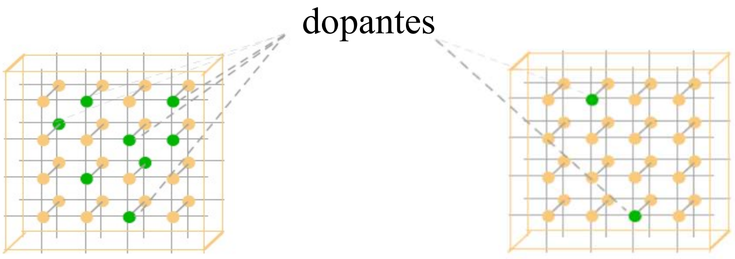


- A partir de 1970, o processo de dopagem passou a ser via implantação iônica com o seguinte aspecto:



Processo de Difusão

- Altas temperaturas: 600-1200 °C
- Equação de Fick
- Perfil de Difusão
- Máscaras para a Difusão

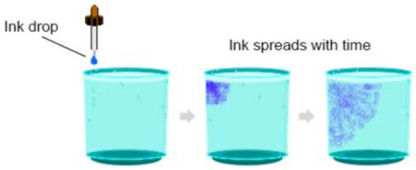


dopantes

alta concentração

baixa concentração

Equação de Fick



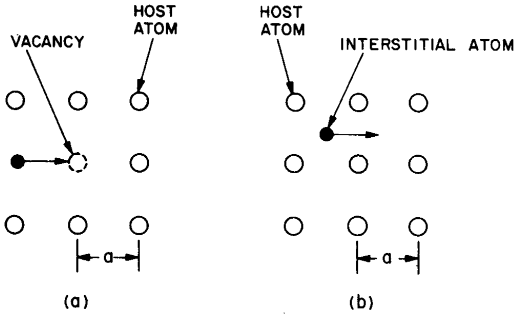
1855 – teoria da difusão

Flux of ink

$$F = -D\frac{\partial C(x,t)}{\partial x}$$

driving force

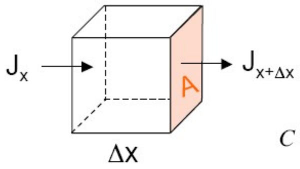
Proportionality constant (Diffusion coefficient)



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}



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

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

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

$$\frac{C_{t+\Delta t} - C_t}{\Delta t} = -\frac{J_{x+\Delta x} - J_x}{\Delta x} \Rightarrow \boxed{\frac{\partial C}{\partial t} = -\frac{\partial J}{\partial x}}$$

Perfil de difusão para fonte infinita (C(0,t)=Cs)

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

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

Table 1 Error Function Algebra

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

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

$$\mathrm{erf}\,(0) = 0$$

$$\mathrm{erf}\,(\infty) = 1$$

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

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

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

$$\frac{d^2}{dx^2}\mathrm{erf}\,(x) = -\frac{4}{\sqrt{\pi}}xe^{-x^2}$$

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

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

Donors (Electron-increasing Dopants)		Acceptors (Hole-increasing Dopants)	
P← As Sb	Column V elements	B← Ga In Al	Column III elements

A difusão ocorre porque há um gradiente de concentração de dopante!

Fonte INfinita de dopantes

Difusion pré-deposição

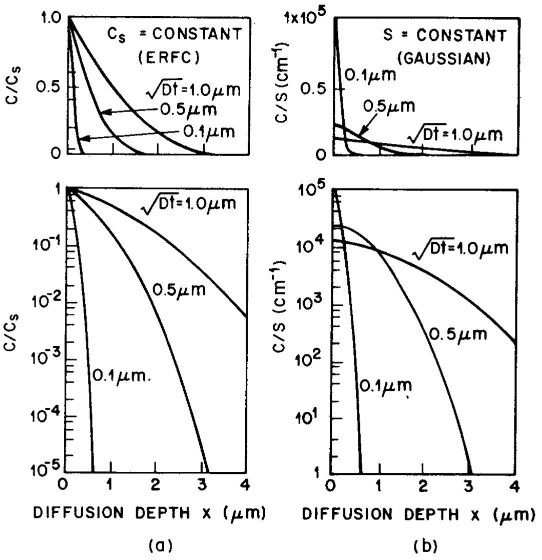


Fig. 4 Diffusion profiles. (*a*) Normalized complementary error function (erfc) versus distance for successive diffusion times. (*b*) Normalized Gaussian function versus distance for successive times.

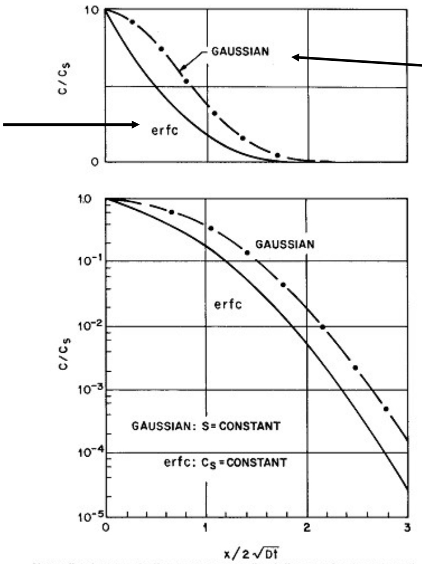
C(x,0)=0

C(x,∞)=t

Fonte Finita de dopantes

Drive-in penetração

Distribuição Gaussiana x erfc



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

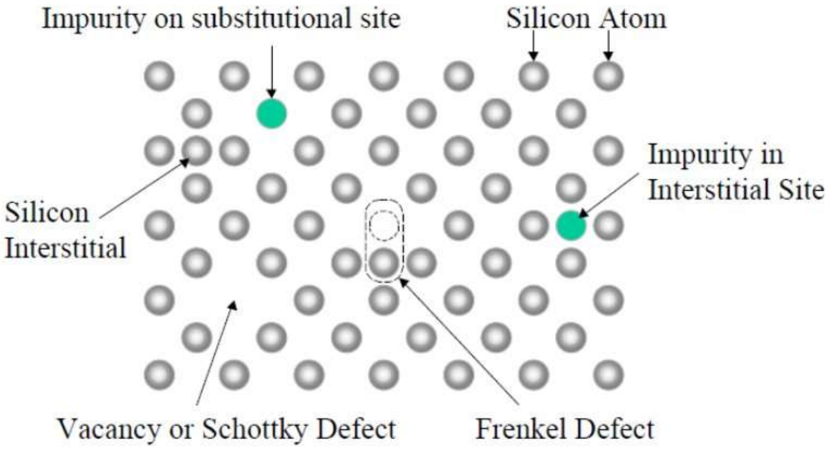
Drive-in
penetração

Difusion
pré-deposição

Drive-in
penetração

Difusion
pré-deposição

Defeitos no silício



Impurity on substitutional site

Silicon Atom

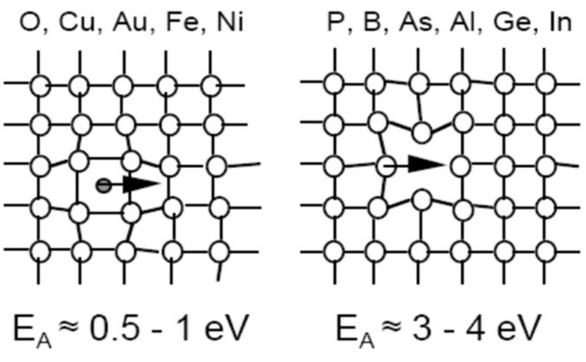
Impurity in Interstitial Site

Silicon Interstitial

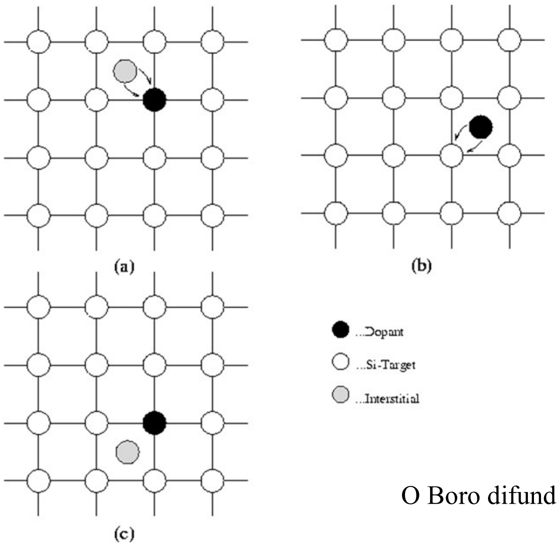
Vacancy or Schottky Defect

Frenkel Defect

Intersticial Vacância



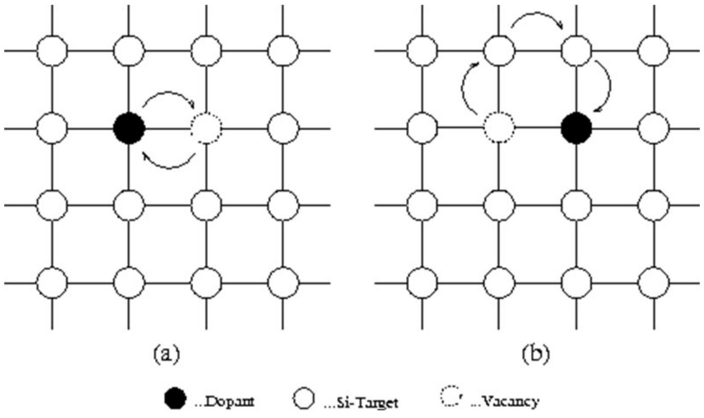
Difusão por posição intersticial



O Boro difunde assim

O dopante é sempre eletricamente ativo

Difusão por vacância



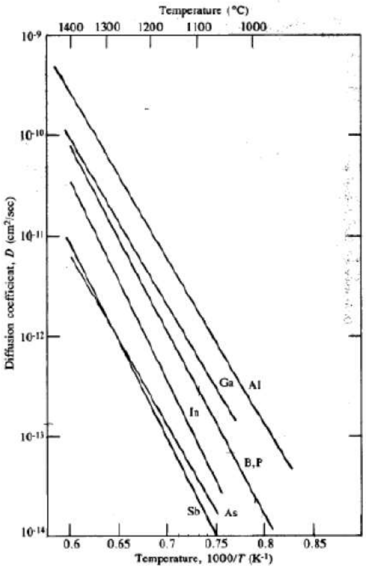
O Fósforo e o Arsênico difundem assim

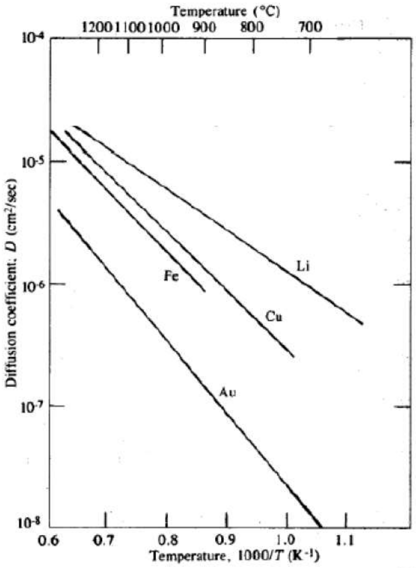
O dopante é sempre eletricamente ativo

Difusão no Silício

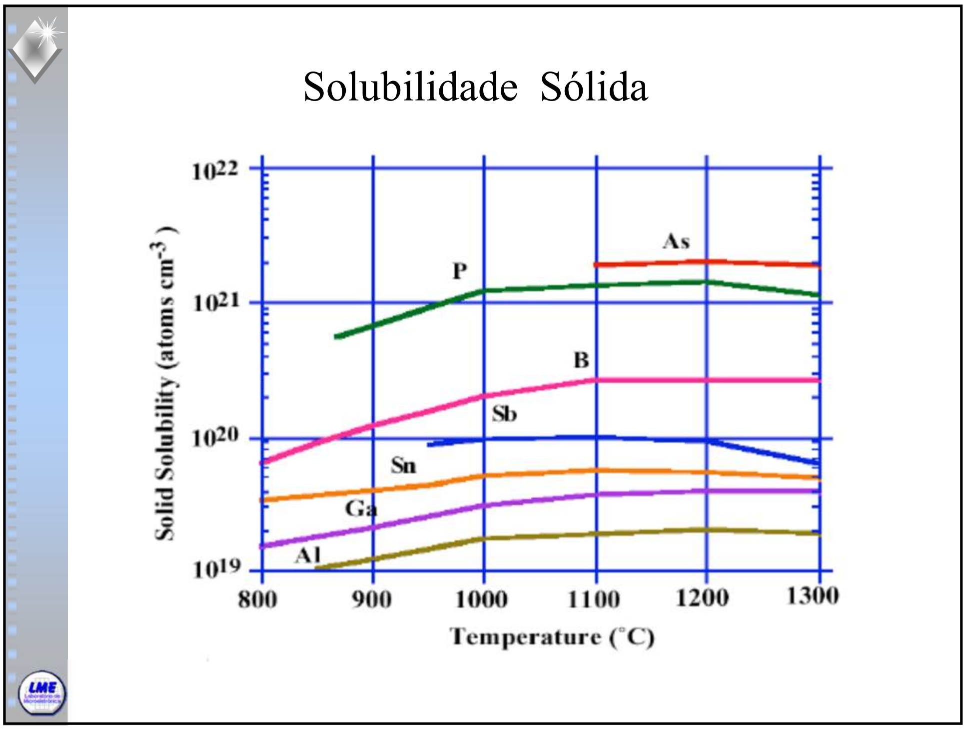
Diffusion of B in Si:

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





Solubilidade Sólida



Difusion (Pré-Deposição)

Fonte **infinita** de dopantes

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

IC $C(x,0) = 0$

BCs $C(0,t) = C_S$

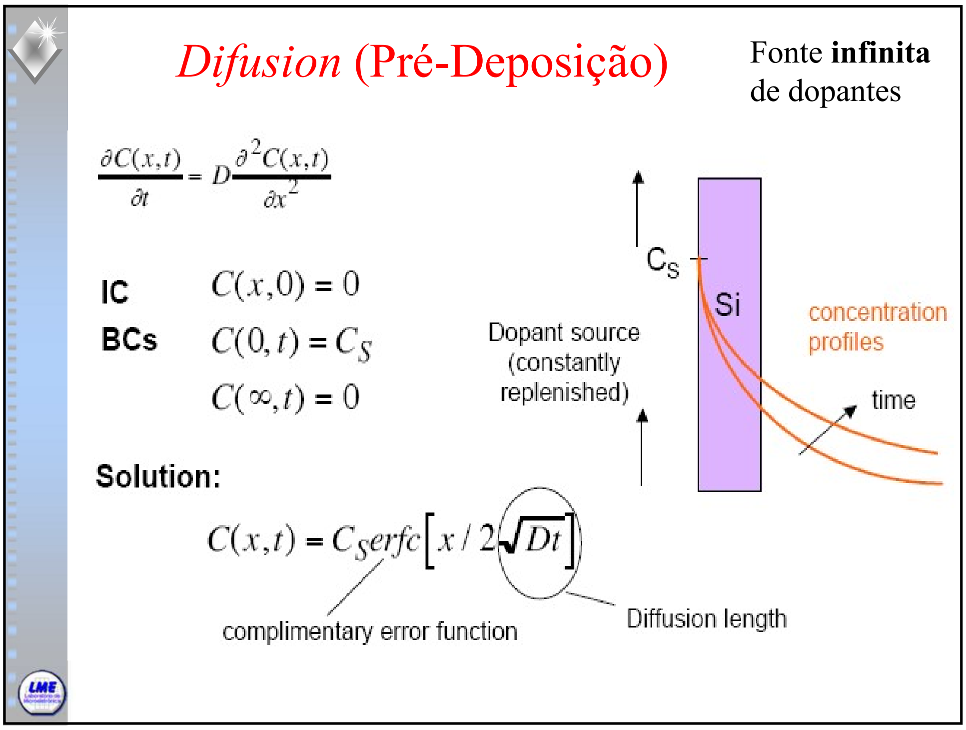
$C(\infty,t) = 0$

Solution:

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

complimentary error function

Diffusion length



Drive-in (Penetração)

Fonte **finita**
de dopantes

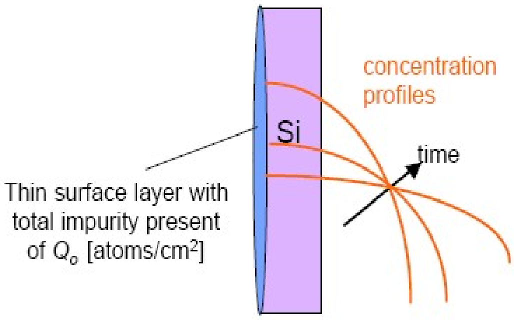
$$\frac{\partial C(x,t)}{\partial t} = D\frac{\partial^2 C(x,t)}{\partial x^2}$$

Dirac delta function

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

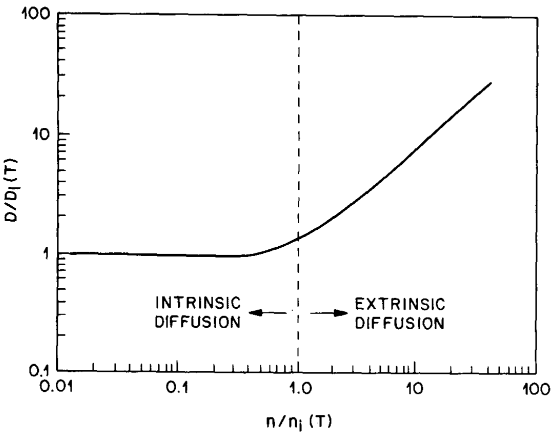
BCs $\frac{\partial C(0,t)}{\partial x} = 0$

$C(\infty,t) = 0$



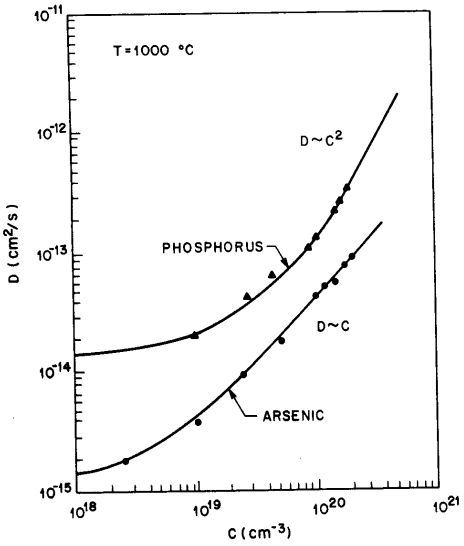
Solution:

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



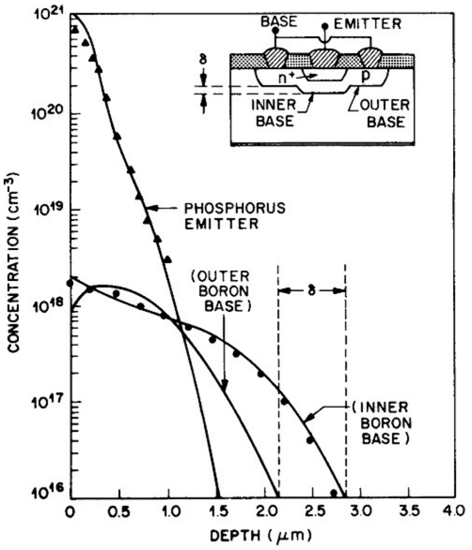
Donor impurity diffusion coefficient versus electron concentration showing regions of intrinsic and extrinsic diffusion.

Difusividade



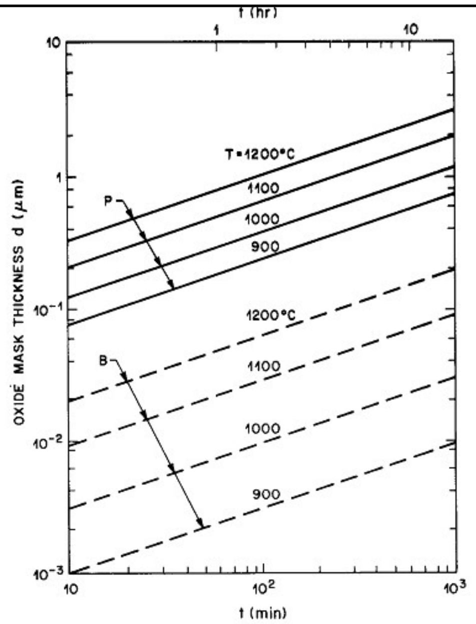
Extrinsic diffusivities of arsenic and phosphorus in silicon as a function of dopant concentration.

Sobreposição de dopagem



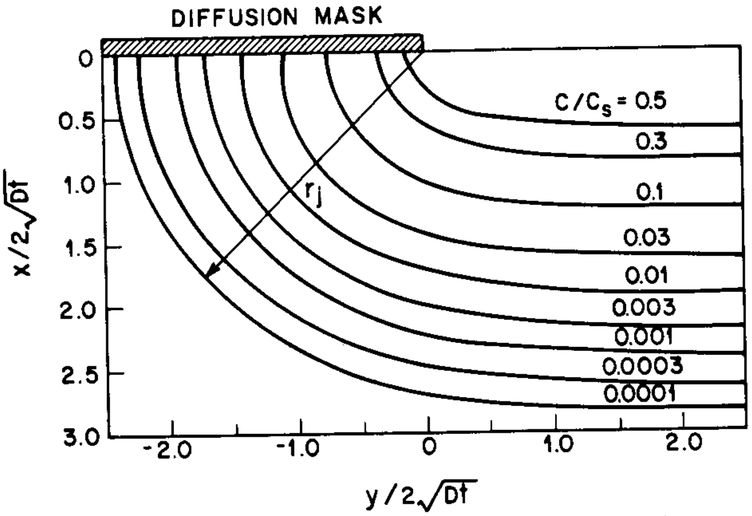
Calculated and measured boron and phosphorus *n–p–n* transistor profile showing the emitter push effect. Emitter diffusion is at 1000° C, for 1 hr, followed by a 900° C, 45-min steam oxidation.

Óxido como Máscara

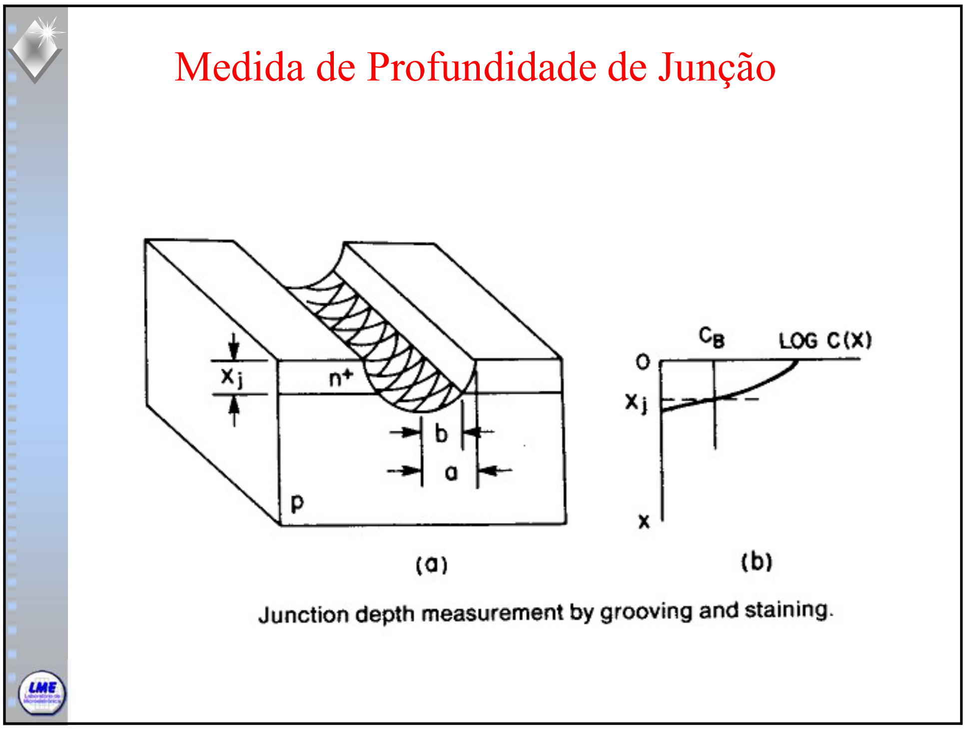


Minimum thickness of dry-oxygen-grown SiO_2 required to mask against phosphorus and boron as a function of diffusion time with diffusion temperature as a parameter.

Difusão Lateral

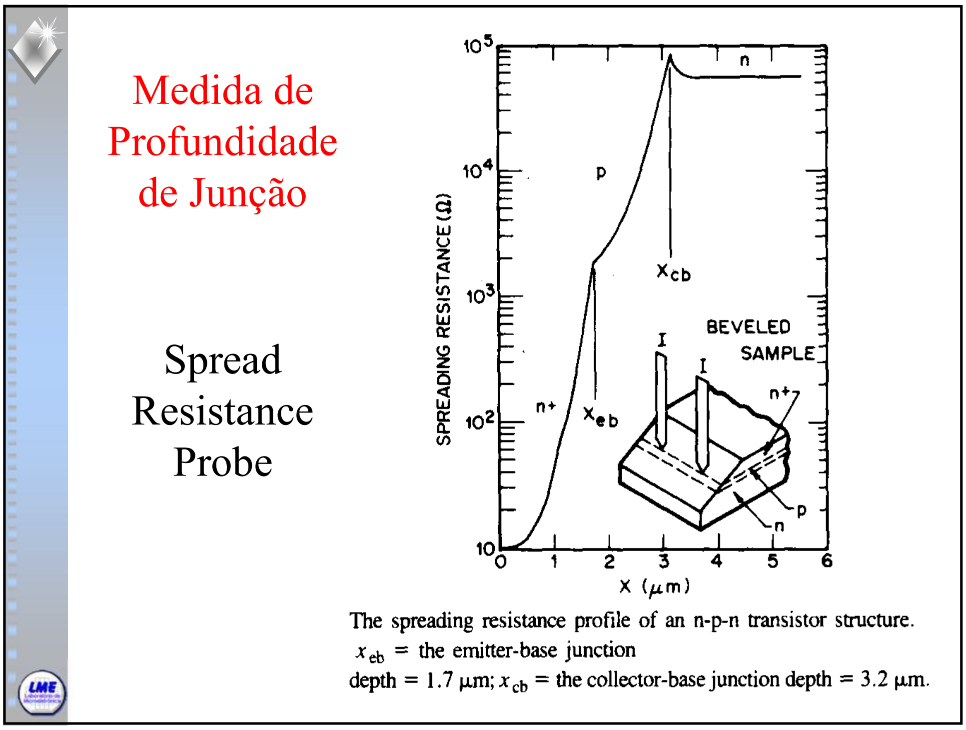


Diffusion contours at the edge of an oxide window, where r_j is the radius of curvature.



Medida de Profundidade de Junção

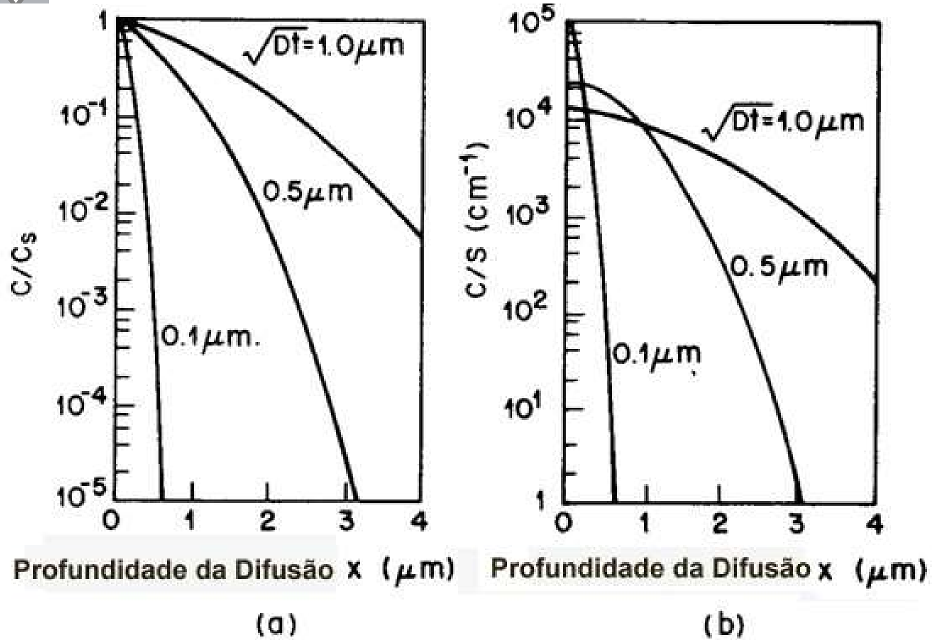
Junction depth measurement by grooving and staining.



Medida de Profundidade de Junção

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.



Difusion (pré-deposição)

Drive-in (penetração)