6.774 Fall 2004: Chapter 7: Dopant Diffusion and Profile Measurement

Thus far we have discussed major topics including:

- Wafer fabrication and cleaning
- Point defects in silicon
- Details of silicon thermal oxidation, including 2D effects

Reminder: course web-site:
http://web.mit.edu/6.774/www/

During the next several lectures, we will discuss the accurate control and placement of active doping regions, through the process of *dopant diffusion.*

Today:
•introduction to diffusion in silicon (Ch. 7)

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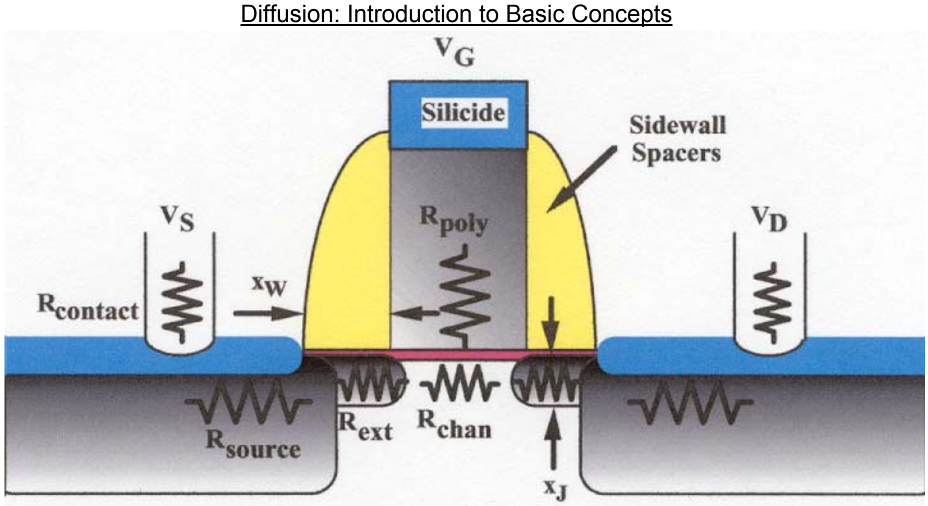
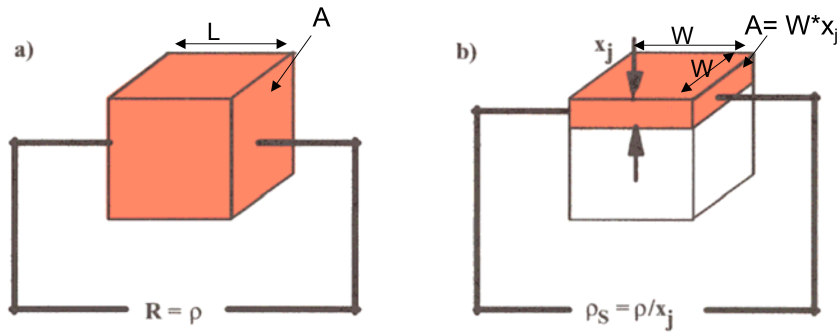
Diffusion: Introduction to Basic Concepts



- Placement of doped regions ('deep' source/drains, source/drain extensions, threshold adjust, etc.) determine many short-channel characteristics of MOSFETs
- Total resistance impacts the current drive
- As device shrinks by a scale factor K, junction depths should also scale by K to maintain same E-field patterns (assuming voltage also scales by K)
- Doping of the polysilicon gate affects gate depletion and limits how well the gate voltage controls the channel potential

General form for resistance: R (ohm) = ρ (ohm-cm) L/A



- The resistivity of a cube is given by

$$J = nqv = nq\mu\mathcal{E} = \frac{1}{\rho}\mathcal{E} \quad \therefore \quad \rho = \frac{\mathcal{E}}{J}\ \Omega\text{cm} \qquad (1)$$

- The sheet resistance of a shallow junction is

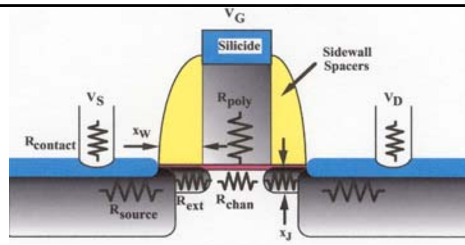
$$R = \frac{\rho}{x_j}\ \Omega/\text{Square} \equiv \rho_S \qquad (2)$$

- **For a non-uniformly doped layer,**

$$\rho_s = \frac{\rho}{x_j} = \frac{1}{q\int_0^{x_j}[n(x) - N_B]\,\mu[n(x)]\,dx} \qquad (3)$$

- **This equation has been numerically integrated by Irwin for different analytical profiles (later).**

- The sheet resistance can be experimentally measured using a four point probe set-up, as discussed previously, or a Van der Pauw structure.



Resistance of the 'extrinsic regions' (i.e. contacts, source and extension) should amount to no more than 10% of the channel resistance:

$$2R_{contact} + R_{source} + R_{drain} + 2R_{ext} < 0.10 (R_{channel})$$

To reduce R_{source}, R_{drain}, R_{ext}, would like to increase x_j

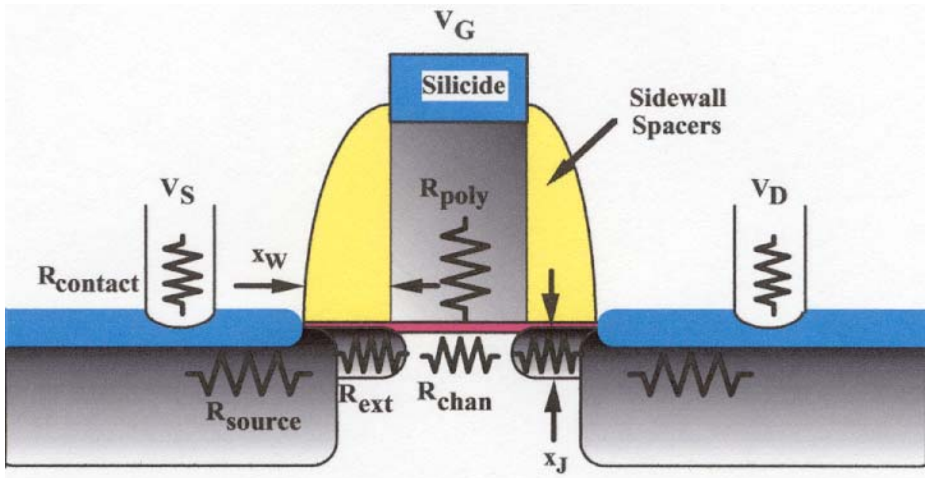
Problem: deeper junctions make it easier for voltages at the drain to affect the current flow in the channel. The 2D spreading of the electric field from the drain can attract carriers from the source, even when the device is supposed to be off: Drain Induced Barrier Lowering (DIBL).

Results in DESIGN TRADEOFF for VLSI MOS devices: series resistance vs. DIBL (current control)

Major challenge: keep the junctions shallow, so DIBL is reduced and at the same time, keep the resistance of the S/D regions small, so that the current drive is maximized. These are CONFLICTING requirements.

Year of 1st DRAM Shipment	1997	1999	2003	2006	2009	2012
Min Feature Size	0.25µ	0.18µ	0.13µ	0.10µ	0.07µ	0.05µ
DRAM Bits/Chip	256M	1G	4G	16G	64G	256G
Minimum Supply Voltage (volts)	1.8-2.5	1.5-1.8	1.2-1.5	0.9-1.2	0.6-0.9	0.5-0.6
Gate Oxide T_{ox} Equivalent (nm)	4-5	3-4	2-3	1.5-2	<1.5	<1.0
Sidewall Spacer Thickness x_W (nm)	100-200	72-144	52-104	20-40	7.5-15	5-10
Contact x_j (nm)	100-200	70-140	50-100	40-80	15-30	10-20
x_j at Channel (nm)	50-100	36-72	26-52	20-40	15-30	10-20
Drain Ext Conc (cm^{-3})	$1x10^{18}$	$1x10^{19}$	$1x10^{19}$	$1x10^{20}$	$1x10^{20}$	$1x10^{20}$

From 1997 SIA NTRS.



• The NTRS requirements in the future will require knowledge of dopant positions with almost atomic-scale accuracy, in 2D and 3D profiles.

• Following are some examples from the present device scaling literature.

Short Channel Effect: source-drain distance is comparable to the MOS depletion width in the vertical direction and the source-drain potential has a strong effect on the control of the current in the device

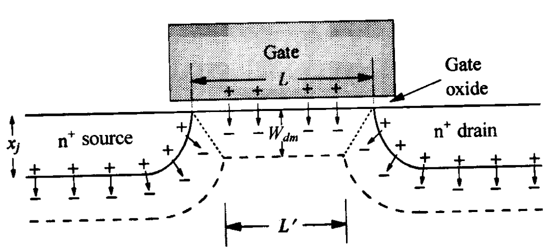
$$\mathbf{V_{TH} = V_{FB} + 2\phi_f + \frac{\sqrt{2\varepsilon_S q N_A (2\phi_f)}}{C_O}}.$$

Constant doping, long channel

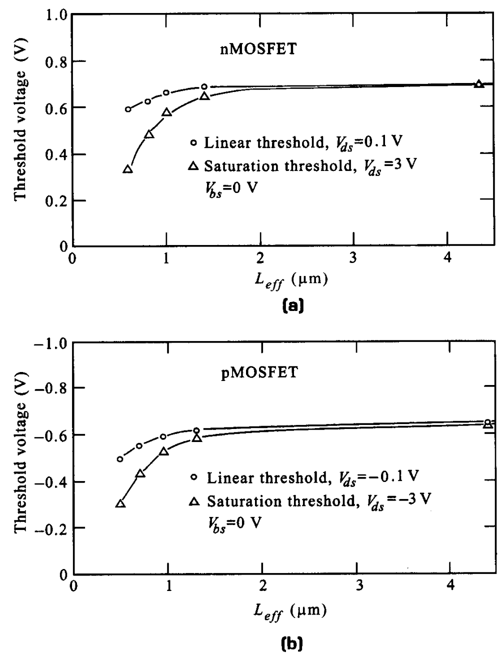
$$V_t = V_{fb} + 2\psi_B + \frac{Q'_B}{WLC_{ox}},$$

Vt is lower

Short channel case

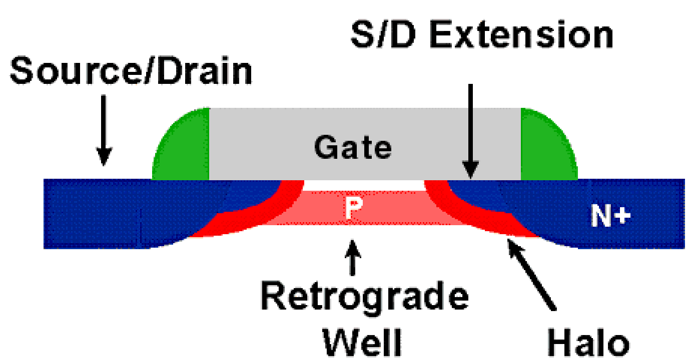


From Y. Taur and T. Ning, Fundamentals Of Modern VLSI Devices, Cambridge Univ. Press, p. 142.



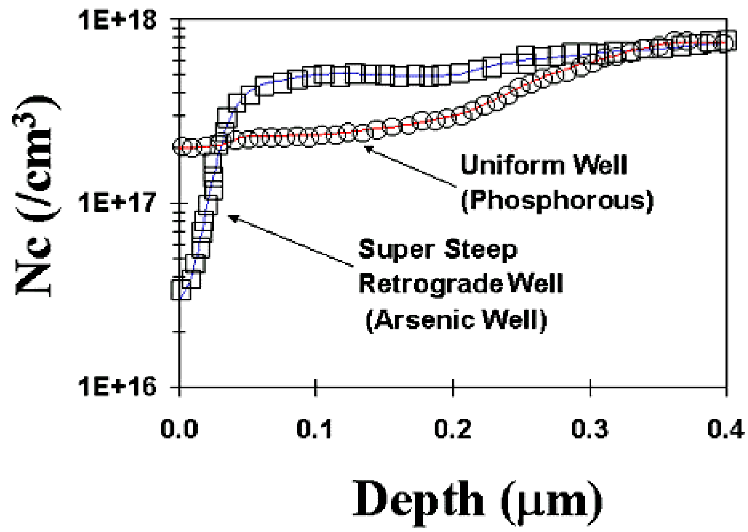
From Y. Taur and T. Ning, Fund. Of Modern VLSI Devices, Cambridge Univ. Press, p. 140.

Channel Doping Profile Engineering: Optimize Final Doping Profiles of the p-type (NMOS) and n-type (PMOS) Dopants in the Channel Region



From Intel article: Thompson, Packan, Bohr, MOS Scaling: "Transistor Challenges for the 21st Century"

http://developer.intel.com/technology/itj/q31998/articles/art_3.htm



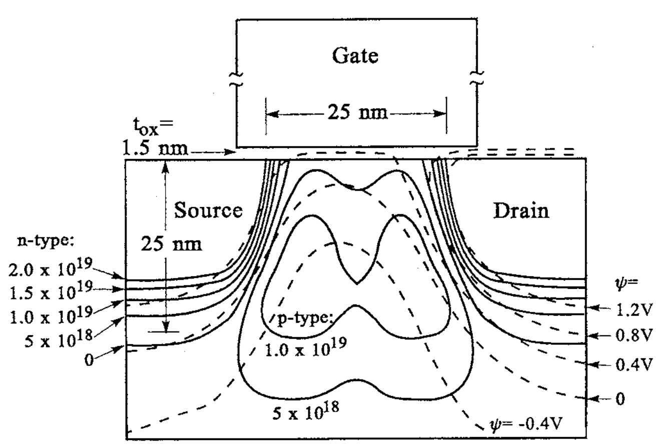
Doping profiles in the channel region provide the same Vt, but better leakage current control (can be scaled to smaller Leff)

http://developer.intel.com/technology/itj/q31998/articles/art_3.htm

Halo or Pocket Profiles: Improve Manufacturability

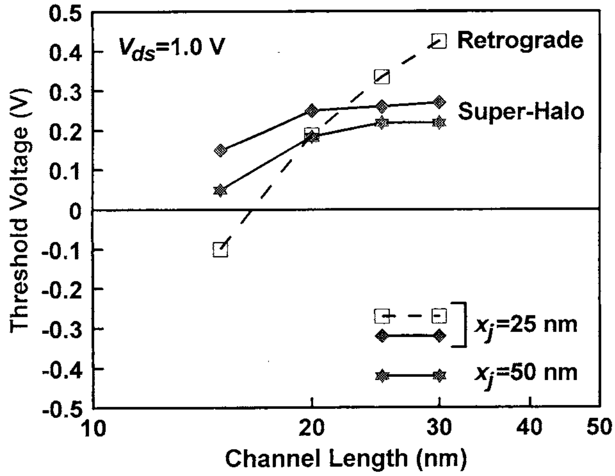
25 nm Gate Length MOSFET Design

Taur, Wann and Frank, IEDM 1998, p. 789.



- **Super-Halo profile (V_{dd} = 1.0 V)**

Short-channel Threshold Voltage Roll-Off (Variation with Channel Length)

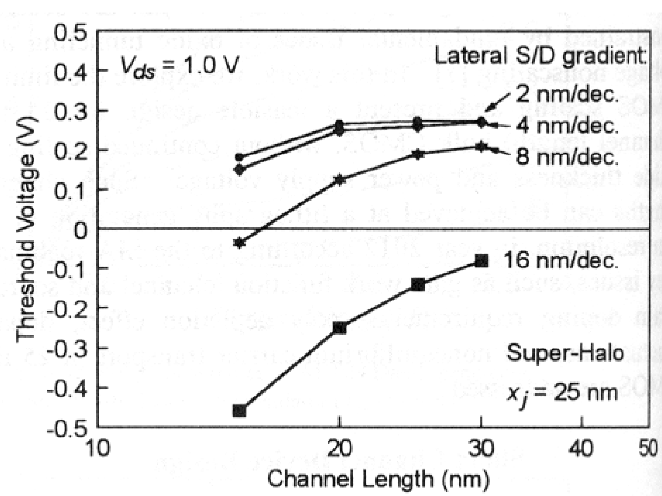


Taur, Wann and Frank, IEDM 1998, p. 789.

- Nearly flat short-channel Vt roll-off with super-halo profile
- Vt roll-off not too sensitive to vertical junction depth

Less variation of Vt with Leff allows larger design window (for process variations), so can push the channel length smaller (not a fundamental improvement in device performance)

Doping Profiles (for S/D dopants) in the Lateral Direction are Becoming Critical



Taur, Wann and Frank, IEDM 1998, p. 789.

Effect of **lateral** source-drain doping gradient on short-channel roll-off. For gradients larger than 4 nm/decade (laterally), the Vt roll-off is too large for a 25 nm MOSFET.

Dopant Diffusion Fundamentals

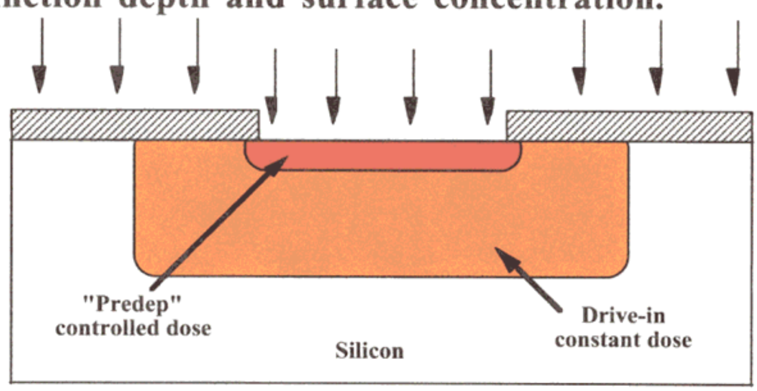
- **Diffusion is the redistribution of atoms from regions of high concentration of mobile species to regions of low concentration. It occurs at all temperatures, but the diffusivity has an exponential dependence on T.**

- **Predeposition: doping often proceeds by an initial predep step to introduce the required dose of dopant into the substrate.**

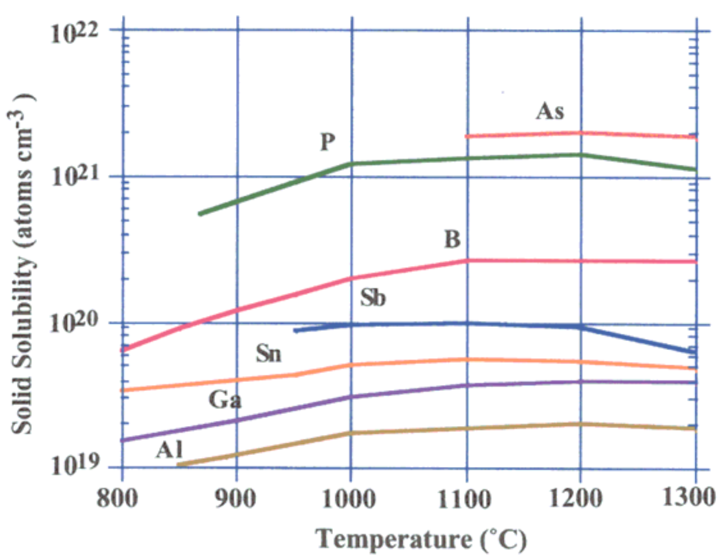
Originally: predeposition was done by diffusion from doped glass layers or by introduction into the Si by heating in a doped gas ambient

Modern: usually done by ion implantation (Chapter 8)

- **Drive-In: a subsequent drive-in anneal then redistributes the dopant giving the required junction depth and surface concentration.**

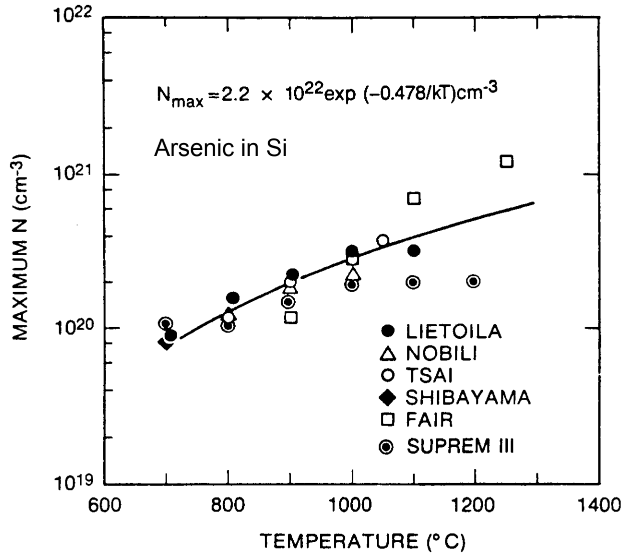


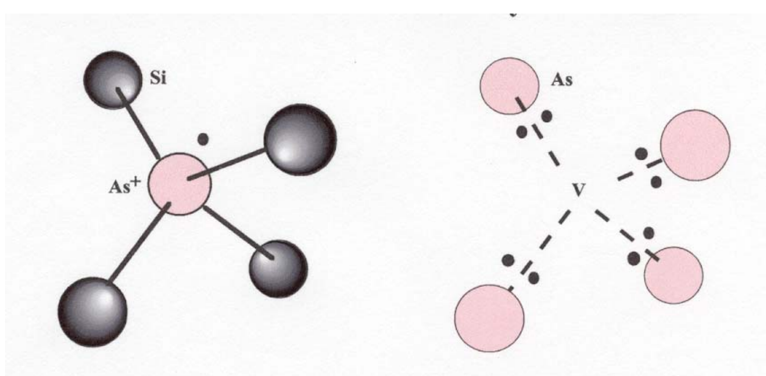
	Ion Implantation and Annealing	Solid/Gas Phase Diffusion
Advantages	Room temperature mask	No damage created by doping
	Precise dose control	Batch fabrication
	10^{11} - 10^{16} atoms cm^{-2} doses	
	Accurate depth control	
Problems	Implant damage enhances diffusion	Usually limited to solid solubility
	Dislocations caused by damage may cause junction leakage	Low surface concentration hard to achieve without a long drive-in
	Implant channeling may affect profile	Low dose predeps very difficult



Dopants are soluble in bulk silicon up to a maximum value before they precipitate into another phase ("solid solubility").

Dopants also have an “electrical” solubility that is different than the solid solubility defined above.



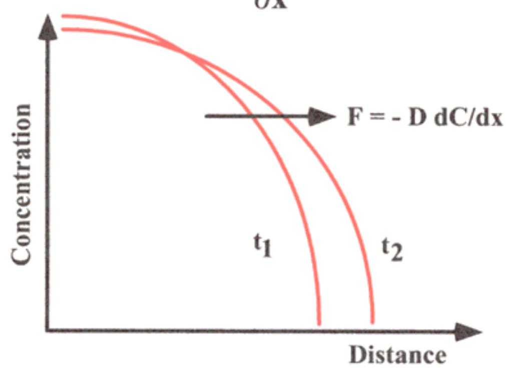


As_4V is a complex which is one possible explanation for the electrically inactive (yet ‘substitutional’) As in silicon, at high As concentrations

First consider macroscopic diffusion (later discuss atomistic diffusion mechanisms and effects).

Macroscopic dopant diffusion is described by Fick's first law, which describes how the flux (flow) of dopant depends upon the doping gradient:

$$F = -D\frac{\partial C}{\partial x}$$



When concentration gradient goes to zero, the flow stops.

$$F = -D\frac{\partial C}{\partial x}$$

This is similar to Fourier's law of heat conduction, or ohm's law for current flow.

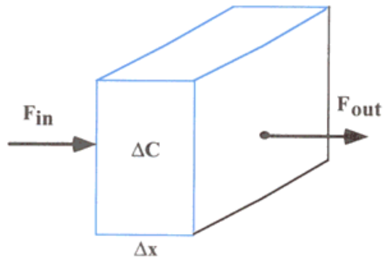
Proportionality constant is the diffusivity D (cm^2/s)

D is related to the atomic hop rate over an energy barrier (formation and migration energies of mobile species) and is exponentially activated (dependent upon temperature). D is isotropic in the silicon lattice (by symmetry).

The negative sign in Fick's first law indicates that the flow is down the concentration gradient.

Fick's Second Law: describes how the change in concentration in a volume element is determined by the change in fluxes in and out of the volume.

$$\frac{\Delta C}{\Delta t} = \frac{\Delta F}{\Delta x} = \frac{Fin - Fout}{\Delta x}$$



- **Mathematically**

$$\frac{\partial C}{\partial t} = \frac{\partial F}{\partial x} = \frac{\partial}{\partial x}\left(D\frac{\partial C}{\partial x}\right)$$

- **If D is a constant this gives**

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

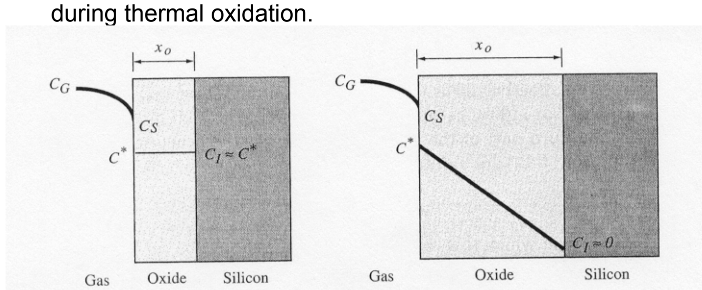
Analytic Solutions of the Diffusion Equation

Steady state: no variation in the concentration with time:

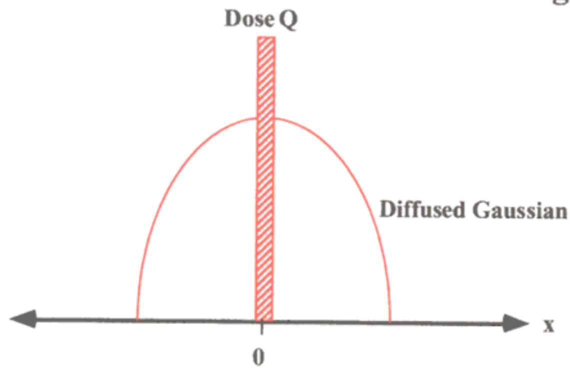
$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} = 0$$

Integrating: C = a + bx (linear profile over distance)

This pertained during solution of diffusion of oxidant through oxide during thermal oxidation.



1. Limited Source: Consider a fixed dose Q, introduced as a delta function at the origin.



Boundary conditions: C --> 0 as t --> 0 for x > 0 (delta function)

C --> infinity at t --> 0 for x=0

$\int C(x,t)\ dx = Q$ (dose= constant)

- **The solution that satisfies Fick's second law is**

$$C(x,t) = \frac{Q}{2\sqrt{\pi Dt}} \exp\left(-\frac{x^2}{4Dt}\right)$$

- **Important consequences:**

1. Dose Q remains constant

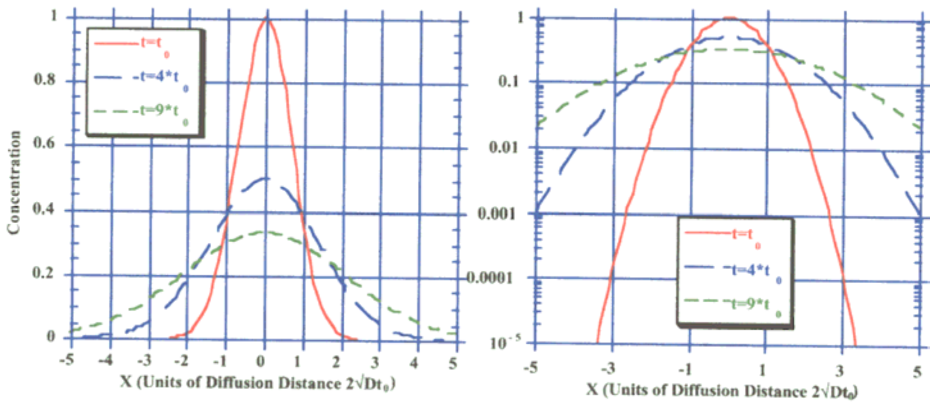
2. Peak concentration decreases as $1/\sqrt{t}$

3. Diffusion distance from origin increases as $2\sqrt{Dt}$

(at this distance, the dopant concentration falls by 1/e)

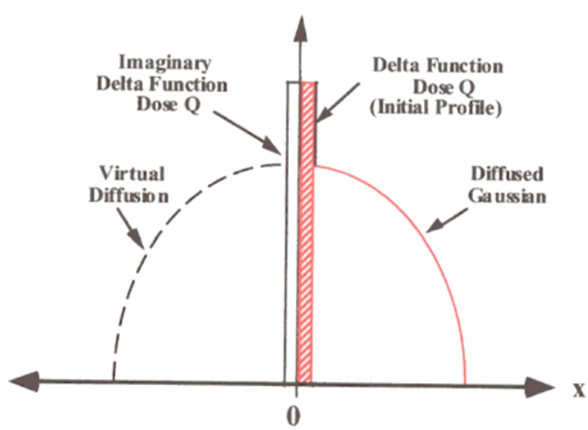
Diffusion length $L = 2\sqrt{Dt}$

Time evolution of a Gaussian diffusion profile

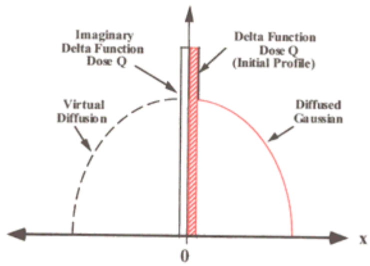


Peak concentration drops by
$1/\sqrt{t}$

2. <u>Fixed Dose Q (constant in time): Diffusion Near a Surface</u>



Assume:
- no dopant lost through evaporation or segregation at the surface
- annealing takes place for a long time, so initial profile is reasonably approximated by a delta function (compared to final profile)



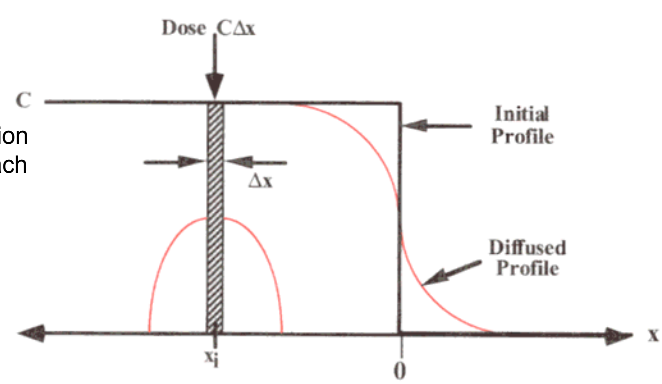
Effectively, dose of 2Q is introduced into a (virtual) infinite medium (by symmetry), so that C(x,t) is given by (Q--> 2Q from previous case):

$$C(x,t) = \frac{Q}{\sqrt{\pi D t}} \exp\left(-\frac{x^2}{4Dt}\right) = C(0,t)\exp\left(-\frac{x^2}{4Dt}\right)$$

Surface concentration

3. Infinite Source: Consider an infinite source of dopant made up of small slices each diffusing as a Gaussian.

Linear superposition of solutions for each of the thin slices:



$$C(x,t) = \frac{C}{2\sqrt{\pi D t}} \sum_{i=1}^{n} \Delta x_i \exp -\frac{(x - x_i)^2}{4Dt}$$

- **The solution which satisfies Fick's second law is**

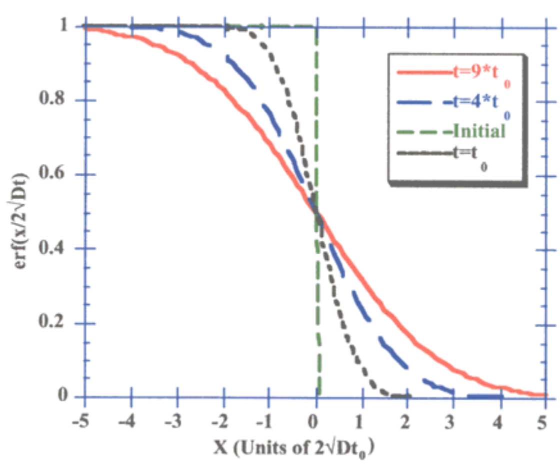
$$C(x,t) = \frac{C'}{2}\left[1 - \mathrm{erf}\left(\frac{x}{2\sqrt{Dt}}\right)\right] = C_S\left[\mathrm{erfc}\left(\frac{x}{2\sqrt{Dt}}\right)\right]$$

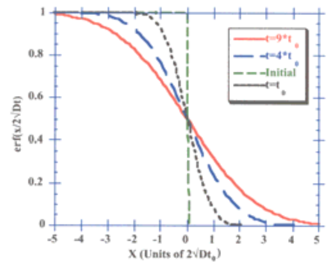
Where:

$$\mathrm{erf}(z) = \frac{2}{\sqrt{\pi}}\int_0^z \exp(-\eta^2)\,d\eta$$

And erfc(x) = 1 - erf(x)

- **Error function solution is made up of a sum of Gaussian delta function solutions.**
- **Dose beyond x=0 continues to increase with annealing time.**





Example: diffusion from a gas ambient into the solid, with the gas concentration above the solid solubility of the dopant

<u>4. Constant Surface Concentration</u>: (just the right hand side of the above figure).

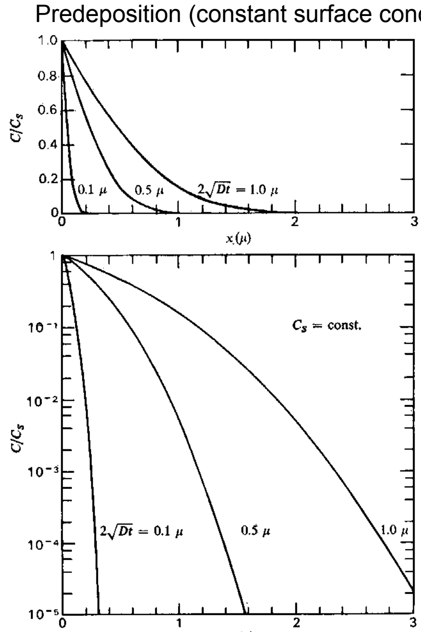
$$C(x,t) = C_S\left[\operatorname{erfc}\frac{x}{2\sqrt{Dt}}\right]$$

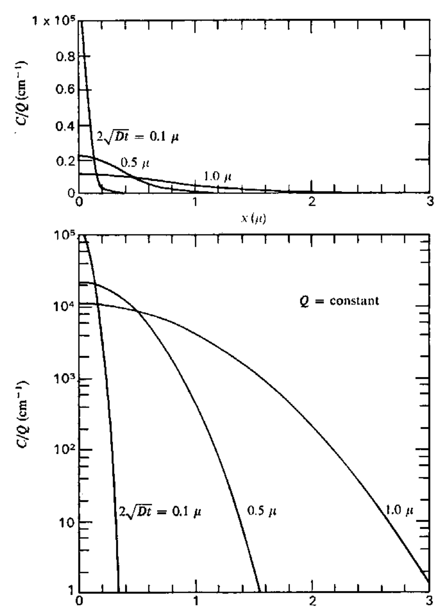
- **Note that the dose is given by**

$$Q = \int_0^\infty C_S\left[1 - \operatorname{erf}\left(\frac{x}{2\sqrt{Dt}}\right)\right] = \frac{2C_S}{\sqrt{\pi}}\sqrt{Dt}$$

Predeposition (constant surface conc.)

Drive-in (constant dose Q)





erfc

Gaussian

Intrinsic Dopant Diffusion Coefficients

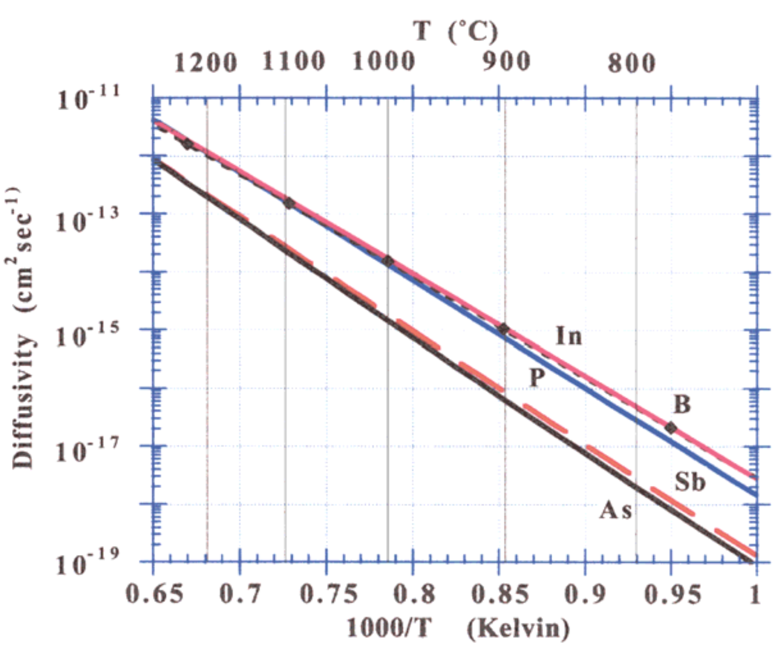
- Intrinsic dopant diffusion coefficients are found to be of the form:

$$D = D^0 \exp\left(\frac{-E_A}{kT}\right) \qquad (13)$$

	Si	B	In	As	Sb	P	Units
D^0	560	1.0	1.2	9.17	4.58	4.70	$cm^2\ sec^{-1}$
E_A	4.76	3.5	3.5	3.99	3.88	3.68	eV

- Note that n_i is very large at process temperatures, so "intrinsic" actually applies under many conditions.

1000C: $n_i \sim 7 \times 10^{18}\ cm^{-3}$



Summary of Introduction to Diffusion

- Placement of doped regions determines many characteristics of short-channel MOSFETs

- There is a design tradeoff between series resistance (needs deeper source-drains), and short-channel effects such as the control of the threshold voltage (needs shallower source-drains)

- Channel doping profile engineering is a way of compromising in this design tradeoff

- The time evolution of dopant profiles, in the simplest cases, is governed by Fick's laws (diffusion equation)

- For a few cases, there are analytic solutions to the diffusion equation:
  - diffusion of a gaussian profile with fixed dose
  - diffusion of an erfc (constant surface concentration)

- Intrinsic diffusion coefficients can be used when the doping is less than n_i at the diffusion temperature