Semiconductor Devices - 2014

Lecture Course
Part of
SS Module PY4P03

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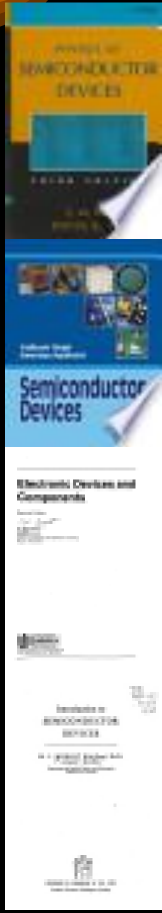
Hilary Term, TCD
13th of Jan ‘14

Recommended Reference Material

- S. M. Sze, *Semiconductor Devices, 2nd edition* (Wiley) 2002
- Y. Singh and S. Agnihotry, *Semiconductor Devices* (I. K. International) 2009
- J. Seymour, *Electronic Devices and components* (Longman) 1988
- M. J. Morant, *Introduction to Semiconductor Devices, 2nd edition* (Harrap) 1970
- Wikipedia* and Encyclopaedia Britannica



Due Thanks and Acknowledgements to

Prof. Eric Finch … who Created This Course…

* With a word of caution!

Lecture Notes, Files, etc.

- Notes will be distributed in hard copy on the day of the lecture
- If you miss a lecture you can still get your hard copy later
- Soft copies will become available after each lecture at:

http://www.tcd.ie/Physics/people/Plamen.Stamenov/Courses.php

- There are two different versions: full colour .pdf and B&W .djvu
- Additional material may be distributed as necessary

Microelectronics Technology Labs

- They should be scheduled in your timetables
- List will be distributed before the classes
- The classes are held in the SNIAM Clean Room
- Led by Dr. Stamenov and four demonstrators
- Each of you will spend nominally two sessions of 3 hours there
- Sessions may need (but hopefully will not) have to be rescheduled upon unplanned circumstances (equipment failures, etc.)

Topics considered I

- Materials
  - Si, SiO_x
  - Ge, SiGe
  - GaAs, Al_xGaAs
  - InP, ZnO, SiC
- Methods and Techniques
  - Crystal growth
  - Diffusion and Implantation
  - Lithography

Topics Considered II

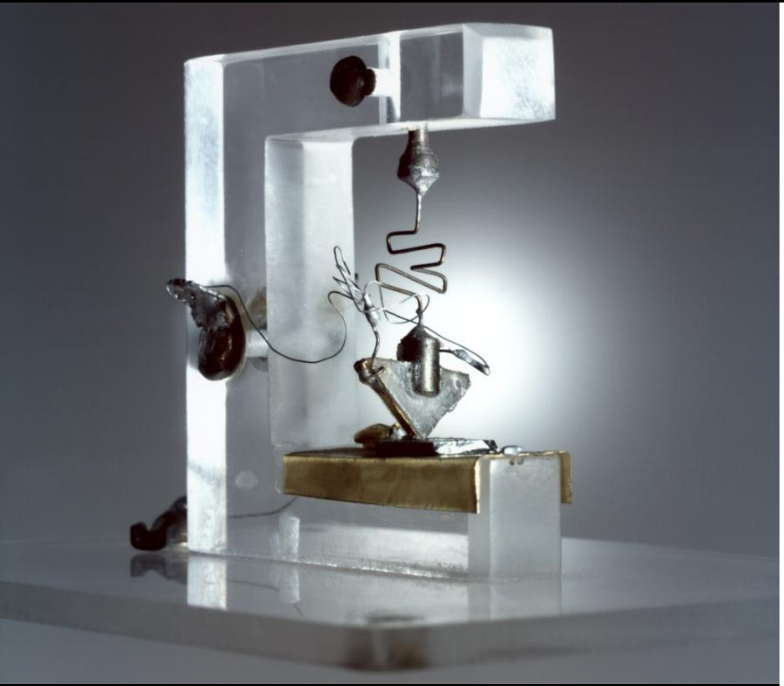
- Structures and Devices
  - Schottky diodes, p-n diodes
  - BPTs, BJTs, MOSFETs, JFETs, MESFETs
  - ICs
  - Gunn and Esaki diodes
- Applications
  - Analogue signals
  - Digital signals
  - Exotics

Key Dates and Names

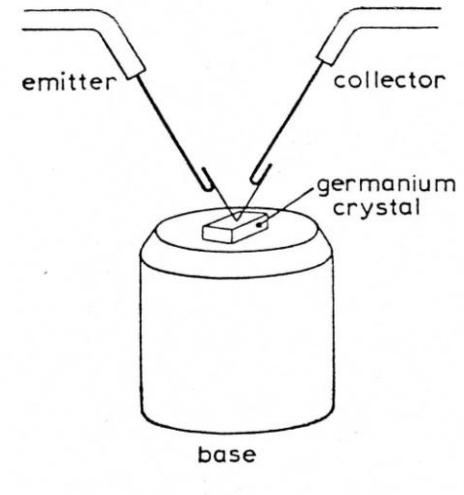
1874	Metal-semiconductor contact (Braun – *NPP1909*)
1947	Bipolar transistor (**Bardeen**, Brattain, Shockley – *NPP1956*)
1949	*p*-*n* junction (Shockley)
1952	Dopant diffusion in silicon (Pfann)
1952	GaAs and other III-V compounds (Welker)
1957	Heterojunction bipolar transistor (Kroemer – *NPP2000*)
1957	Lithographic photoresist (Andrus)
1957	Oxide masking (Frosch and Derrick)
1957	CVD epitaxy (Sheftal, Kokorish, Krasilov)
1957	Esaki diode (Esaki – *NPP1973*)
1958	Ion implantation (Shockley)
1959	Integrated circuit (Kilby, Noyce – *NPP2000*)
1960	MOSFET (Kahng, Atalla)
1960	Planar process (Hoerni)
1963	Gunn device (Gunn)

The First Transistor…

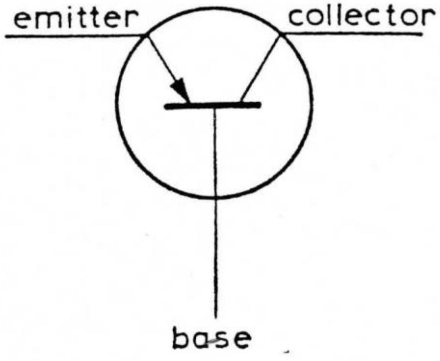
Europe missed it by a little...



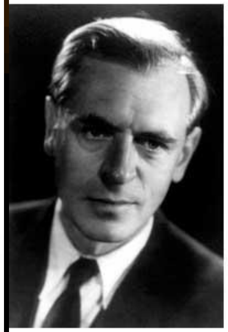
John Bardeen: an Extraordinary Physicist, Physics World, **21**, 4 (April 2008) 22-28

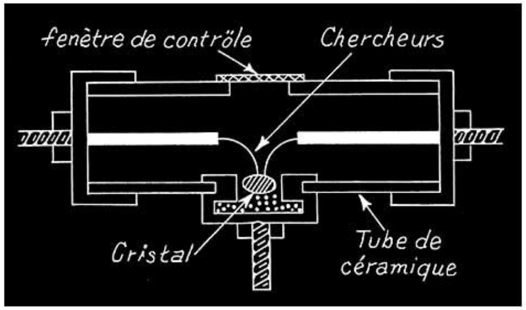


(*a*) Construction of the original point-contact transistor



(*b*) Symbol

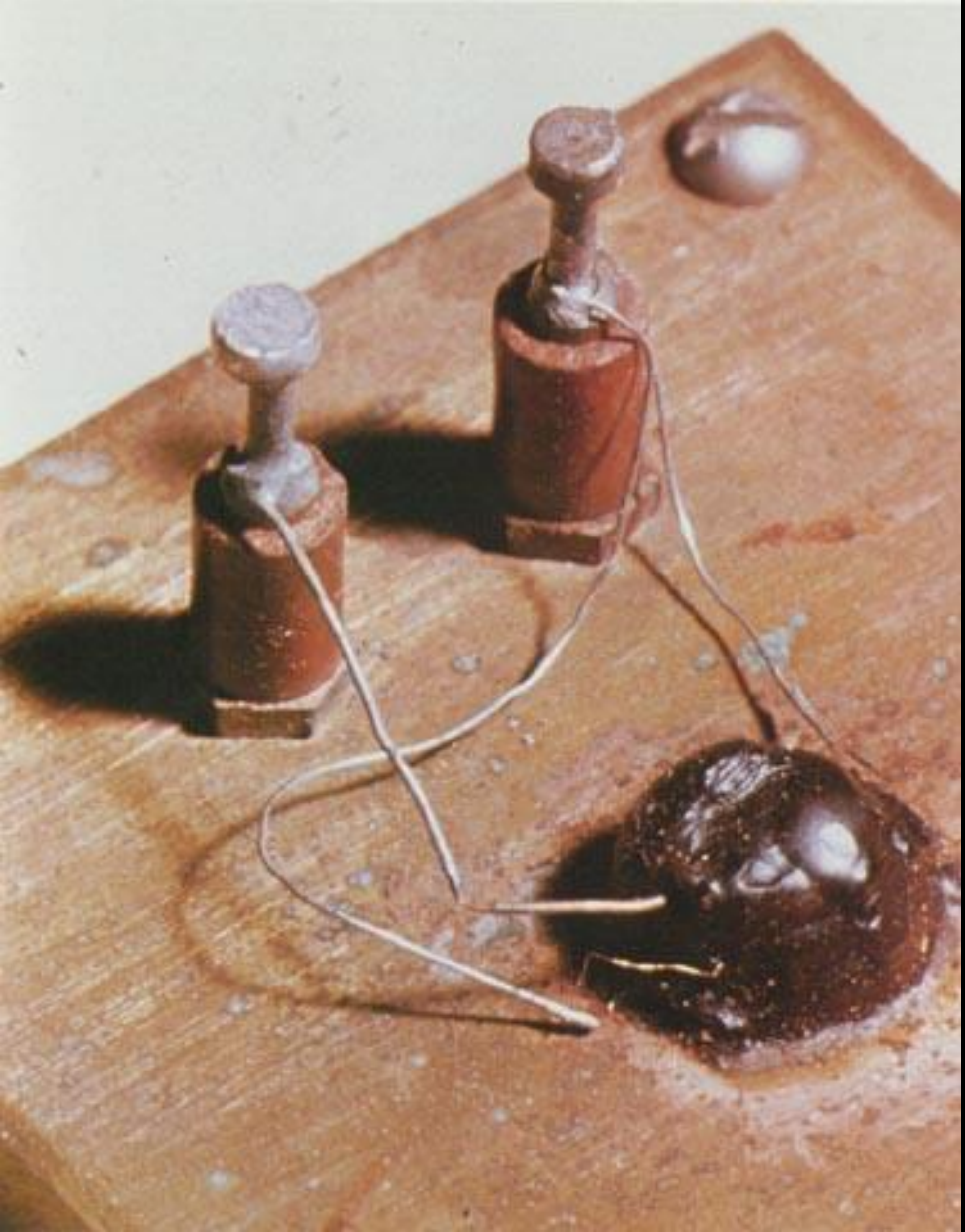


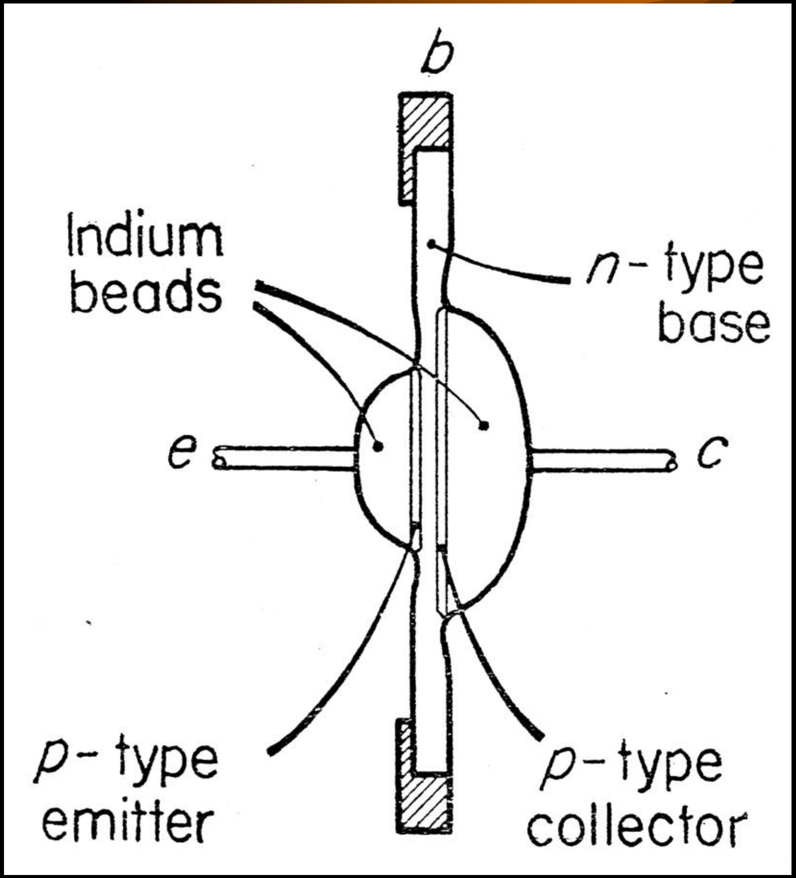


Herbert Mataré and Heinrich Welker and the Transistron

The 'French' Transistor Proceedings of the 2004 IEEE Conference on the History of Electronics

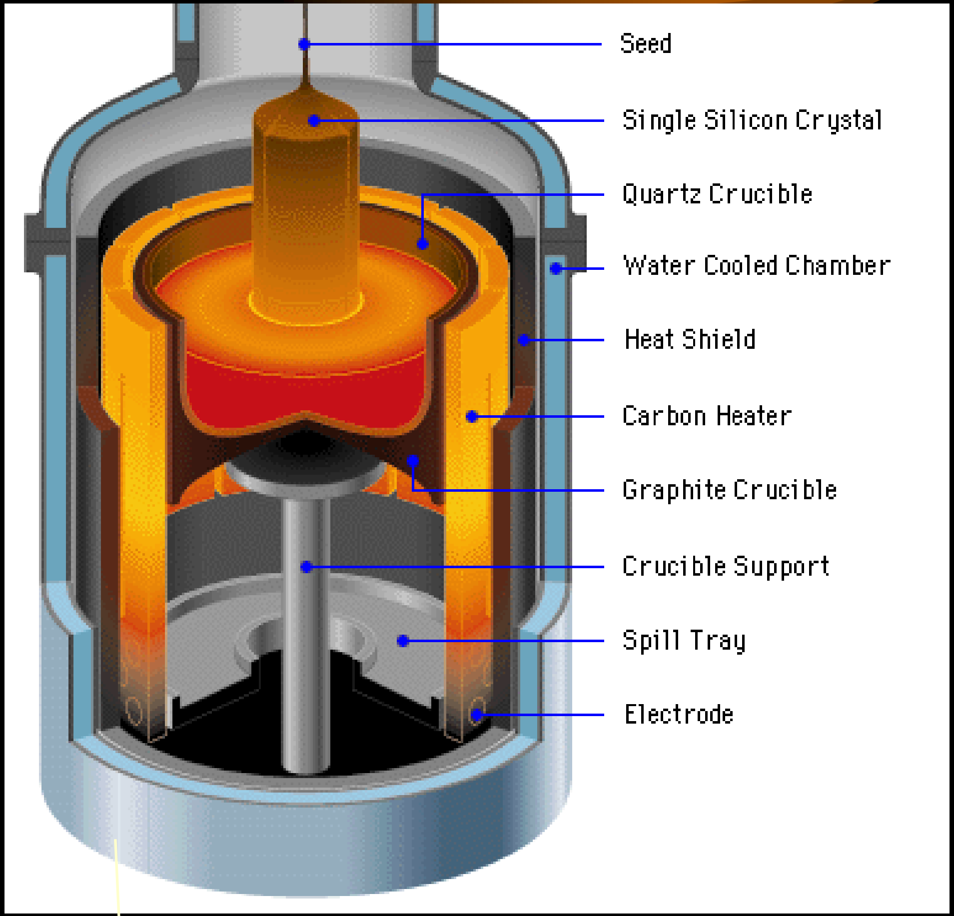
The First Alloy Transistor...





The first germanium alloy transistor, designed by Shockley, 1950

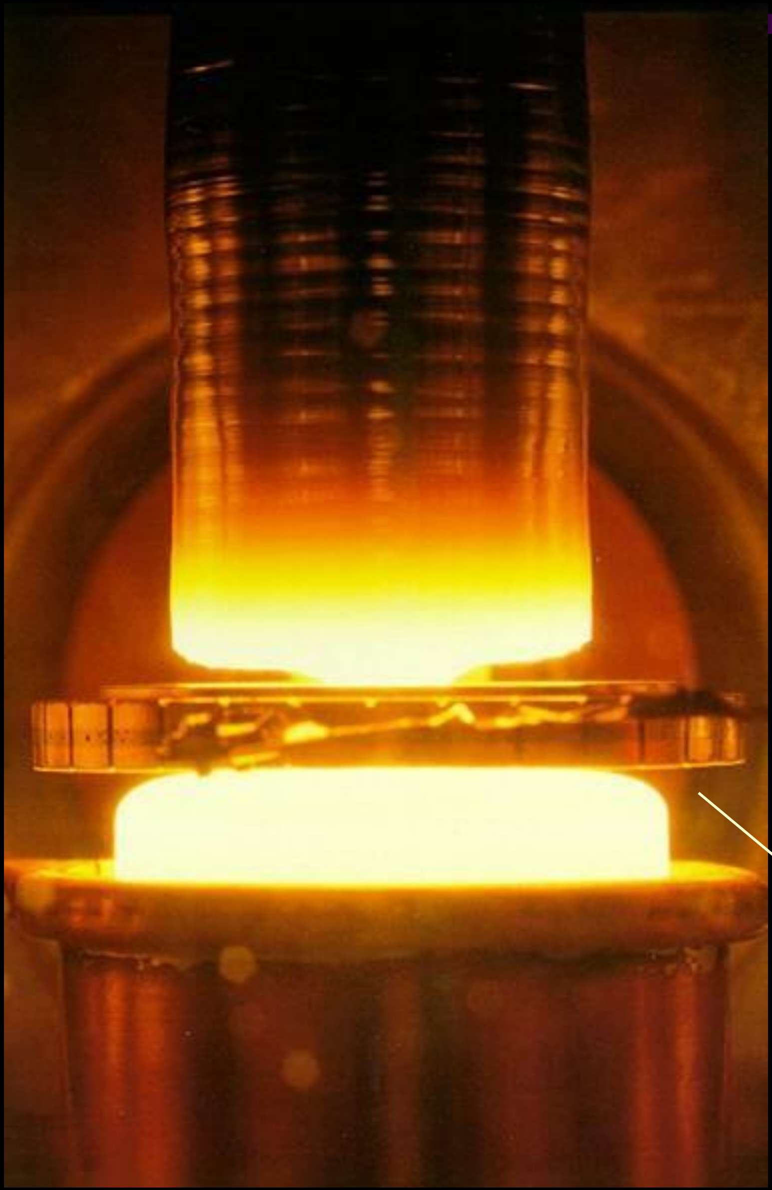
Czhohralski Pulling



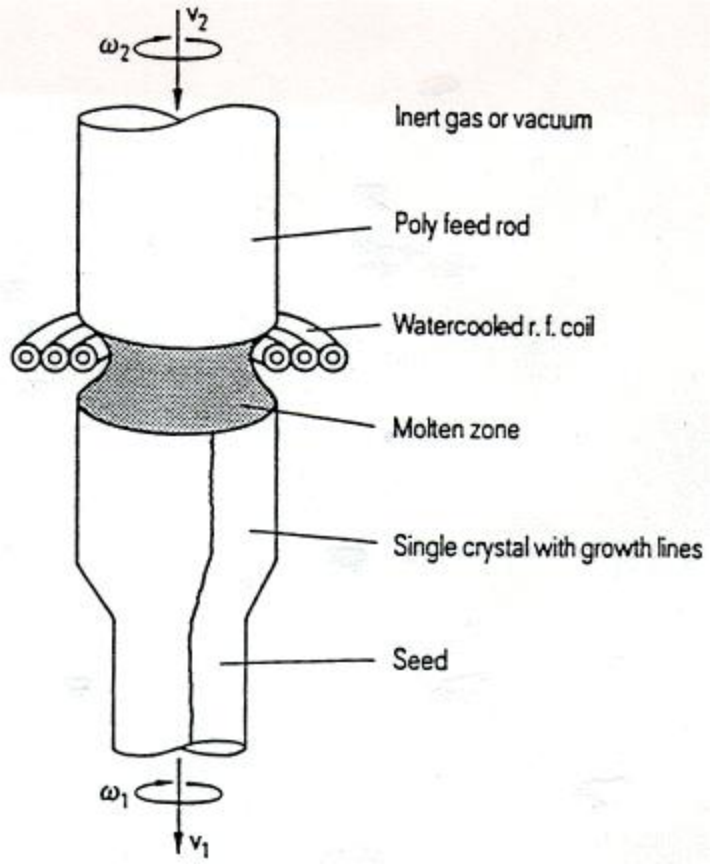
http://people.seas.harvard.edu/~jones/es154/lectures/lecture_2/materials/materials.html

The Dominant Method!
Relatively Fast, Highly Perfected
Economy of Scale.

Molten Zone Refinement



http://www.topsil.com

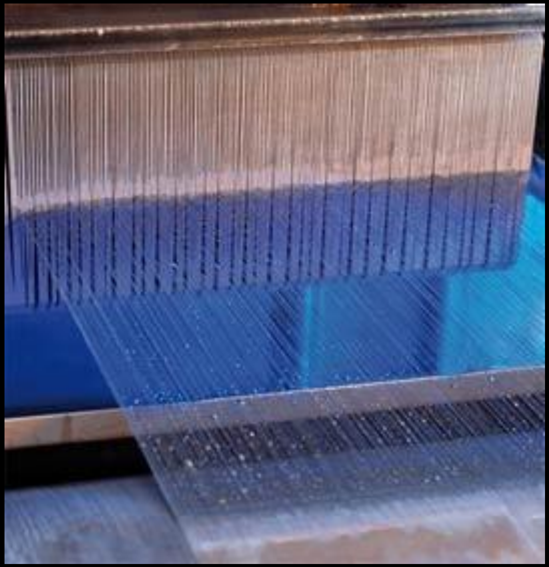


Better but more expensive.
Used when necessary.

Wafer Preparation

- An ‘orientation’ flat or groove is machined in the ingot – four point conductivity and other testing and quality grading is performed.
- Wafer blanks are sliced – usually using diamond wire saws. Thicknesses vary from about 0.3 mm for the small wafer sizes (1 inch) to about 0.8 mm for the largest sizes (12 inch).
- The blanks are polished first mechanically – ‘lapped’ with diamond paste to better than 3 μm tolerance.
- Combination of diffusion-controlled oxidation and diffusion-controlled etching (typically buffered HF + AF solution) until the wafers are close to atomically smooth.
- Oxidation and preparation of Silicon on Insulator (SOI), if required.
- The wafers are ready for device manufacturing
- About 100,000 metric tonnes of pure silicon are produced annually, but less than half of that is monocrystalline – the rest is destined for solar cell manufacturing.

Cutting and Lapping

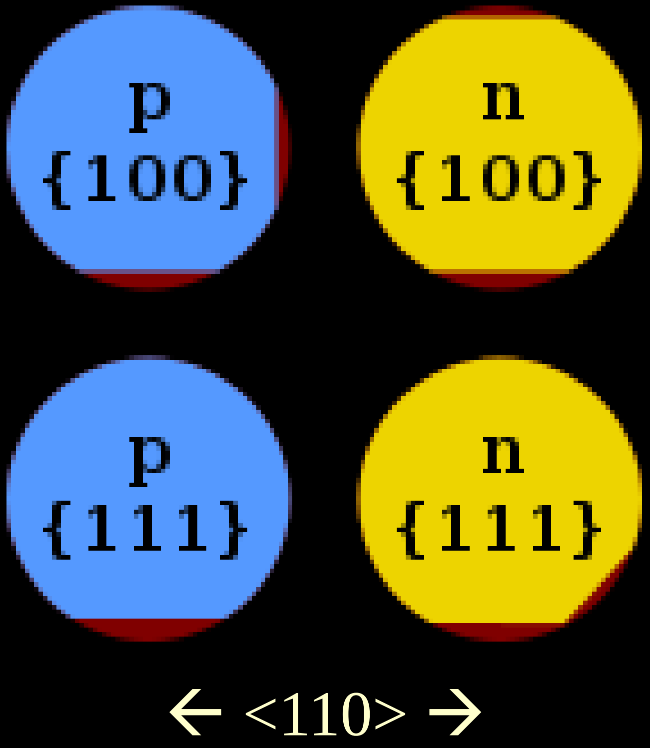


Modern devices are created ‘on-the-surface’ ... and perfect surface is very important...

http://www.solarserver.com

Wafer sizes and Orientation

- 1-inch (25 mm). No standardized thickness. Obsolete for Si.
- 2-inch (51 mm). Thickness 275 µm.
- 3-inch (76 mm). Thickness 375 µm.
- 4-inch (100 mm). Thickness 525 µm.
- 5-inch (130 mm) or 125 mm (4.9 inch). Thickness 625 µm.
- 150 mm (5.9 inch, usually referred to as "6 inch"). Thickness 675 µm.
- 200 mm (7.9 inch, usually referred to as "8 inch"). Thickness 725 µm.
- 300 mm (11.8 inch, usually referred to as "12 inch"). Thickness 775 µm.
- 450 mm ("18 inch"). Thickness 925 µm (expected, but postponed a couple of times for technical reasons and because of high capital investment cost).



Orientation notches ONLY, for most of the bigger sizes.

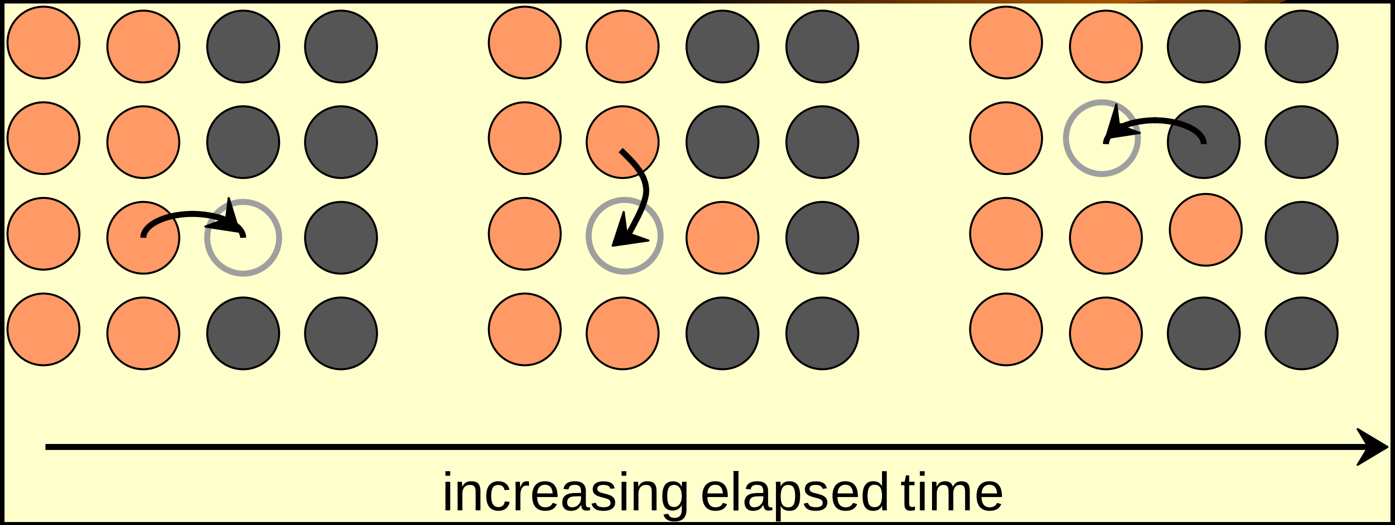
Mechanisms for Diffusion

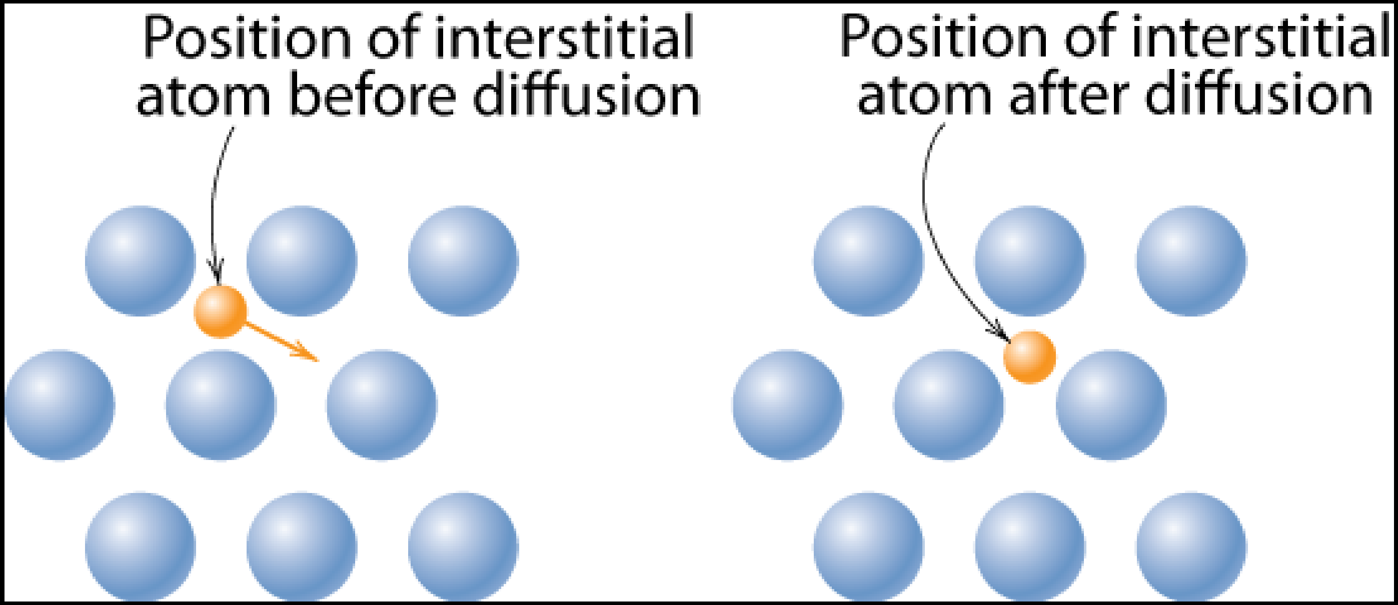
Vacancy Diffusion

- Atoms swap with vacancies
- Works with substitutional impurities
- The rate depends on vacancy concentration

Interstitial Diffusion

- Atoms have to be small
- Important particularly for non-electroactive species
- More rapid





Interstitialcy Component

Fraction measured at 1100 ^{o}C in Silicon:

Al	0.7	p
Sb	0.2	n
As	0.4	n
B	0.8	p
Ga	0.6	p
In	0.5	p
P	0.5	n

Diffusion via the Vacancy Mechanism

Diffusion via the Interstitial Mechanism

Such differences can be very important for the choice of dopant and temperature treatment regime – in the preparation of complex depth profiles

Other factors, such as concentration, level of oxidation, strain, etc. can also affect the interstitialcy component fraction and the activation barriers for diffusion for each of the components!

Diffusion – Fick's First Law

- Diffusion is the process of mass transport driven by concentration gradients.
- The particles (impurities, molecular species, etc.) move in a random fashion from regions of high concentrations to regions of low concentration, so as to 'smooth' the concentration profile.
- The particle flux is described (within a linear approximation) by the first Fick's law :

$$\mathbf{J} = -\hat{\mathbf{D}} \frac{\partial N}{\partial \mathbf{x}}$$

Particle Flux, measured in:
$m^{-2}.s^{-1}$, $mol.m^{-2}.s^{-1}$, $kg.m^{-2}.s^{-1}$

Concentration
m^{-3}, $mol.m^{-3}$, $kg.m^{-3}$

Diff. Coefficient
$m^2.s^{-1}$

- The Diffusion Tensor is represented by a positively-definite symmetric matrix.
- In most cases, however, diffusion is considered isotropic and represented by a single scalar coefficient *D*.
- In one dimension the above equation (for a stationery process) is simply:

$$J_x = -D_x \frac{\partial N}{\partial x}$$

Diffusion – Second Fick's Law

- The temporary dynamics of diffusion is governed by the Second Fick's Law:

$$\frac{\partial N}{\partial t} = \nabla.(\mathbf{D}\nabla N) \approx \mathbf{D}\Delta N$$

- Or, in one dimension, and for constant and homogenous diffusion coefficient:

$$\frac{\partial N}{\partial t} = D_x \frac{\partial^2 N}{\partial x^2}$$

- Obviously, *D* can be a function of the intensive parameters of the system, in particular , it is a rather strong function of temperature.

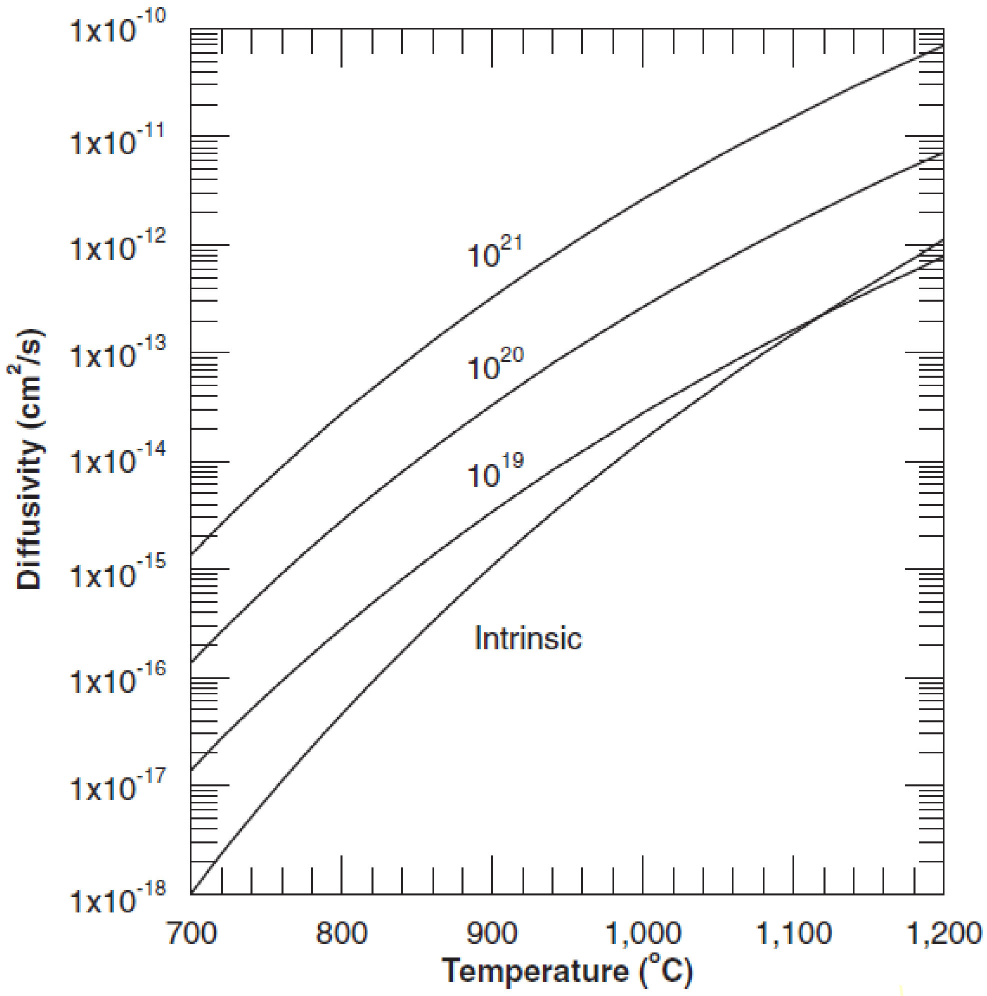
Ideal Gas Constant
$\mathrm{J.K^{-1}, J.K^{-1}(mol,kg)^{-1}}$

$$D(T) = D_0 \exp\left(-\frac{E_A}{RT}\right)$$

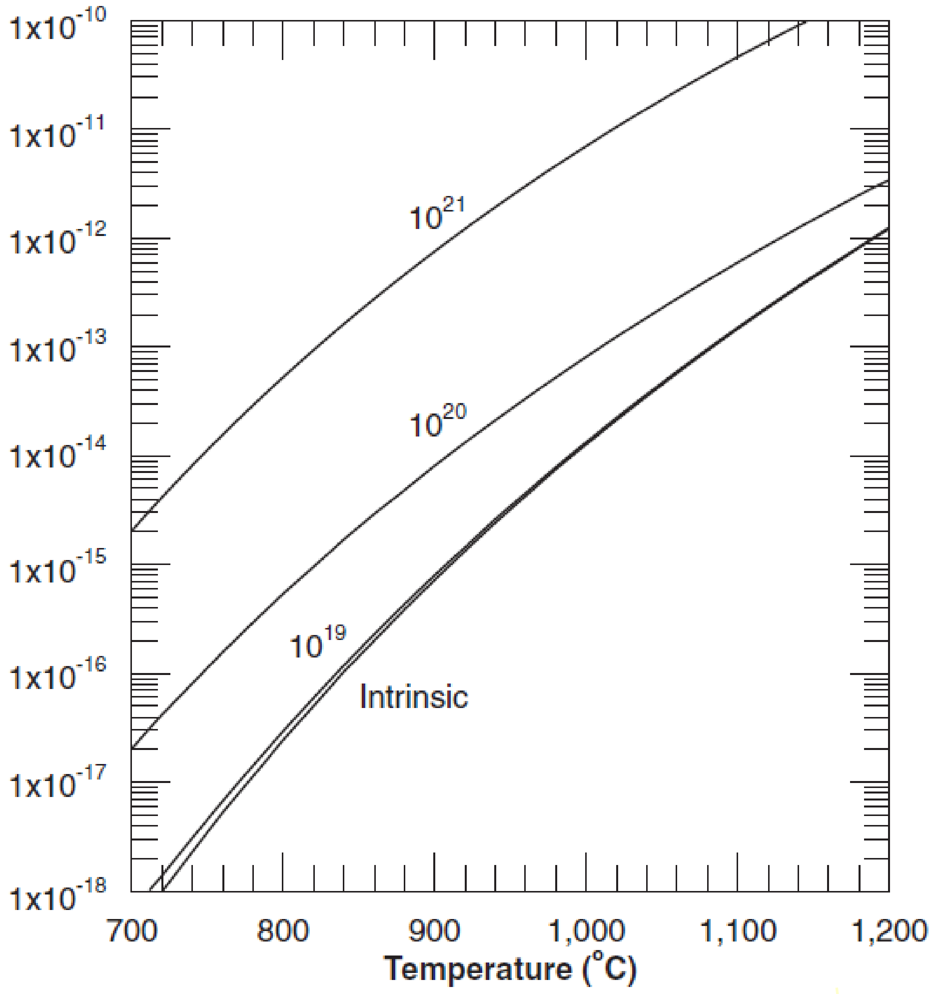
Activation energy
$\mathrm{eV, J.mol^{-1}, J.kg^{-1}}$

- Depending on the diffusing species and the matrix into which they diffuse , the diffusion coefficient can double in a couple of degrees of temperature increment.
- In solids, *D* is typically significant only well above room temperature (hundreds to thousands centigrade) – rapid cooling down to room temperature can 'freeze' dopant distributions – i.e. Rapid Thermal Annealing (RTA).

Fitted Diffusivity Activations



Diffusivity of B in Si



Diffusivity of P in Si

Diffusion From a Constant Source

Approximate Solution

$$N(x,t) \xrightarrow[x \gg 0,\, N \to 0]{} N_0 \operatorname{erfc} a$$

Diffusion Length

$$a = \frac{x}{2\sqrt{Dt}}$$

Complementary Error Function

$$\operatorname{erfc} a = 1 - \operatorname{erf} a$$

Normalized Error Function

$$\operatorname{erf} a = \frac{2}{\sqrt{\pi}} \int_0^a \exp(-b^2)\,\mathrm{d}b$$

$$N(x,t) \xrightarrow[a \gg 1]{} N_0 \frac{1}{a\sqrt{\pi}} \exp\left(-a^2\right)$$

Further Approximation leads to a Gaussian

Diffusion From a Limited Source

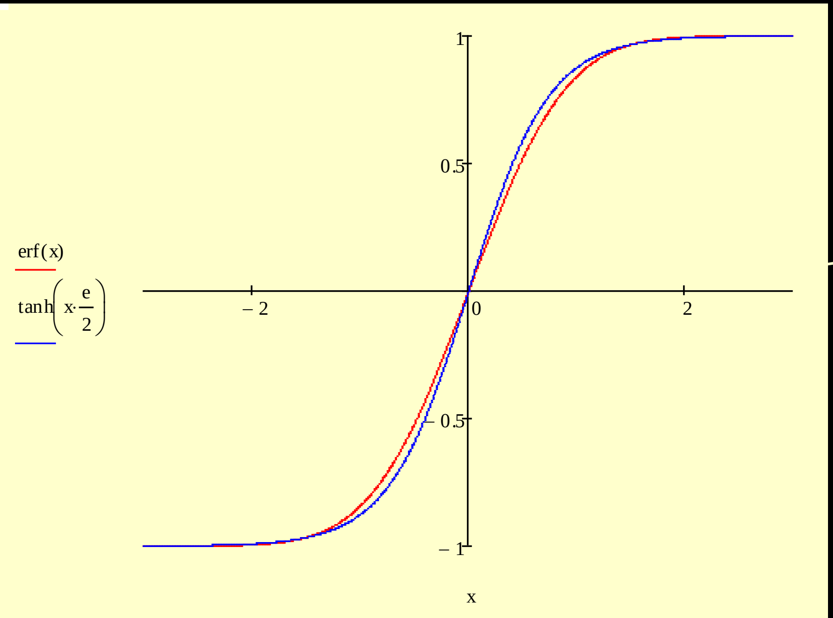
Amount of matter in the Source

$$N(x,t)\xrightarrow[x\gg 0,N\to 0]{}\frac{Q}{\sqrt{\pi D t}}\exp\left(-\frac{x}{4Dt}\right)$$

Another Approximation far From the Source

$$\int_0^\infty N(x,t)\mathrm{d}x = Q$$

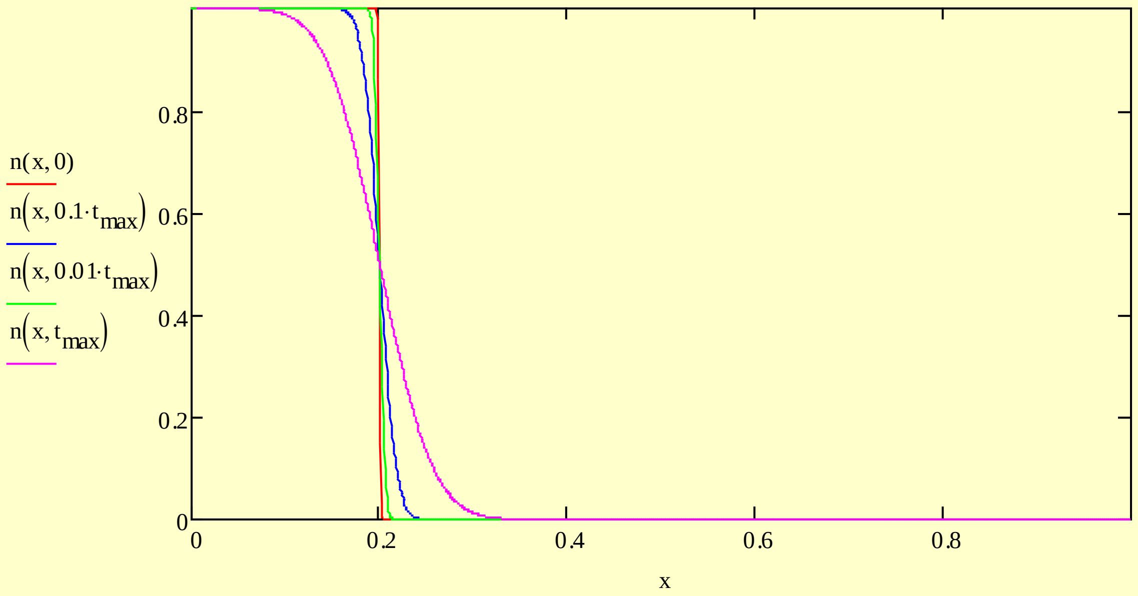
The total amount of matter is conserved



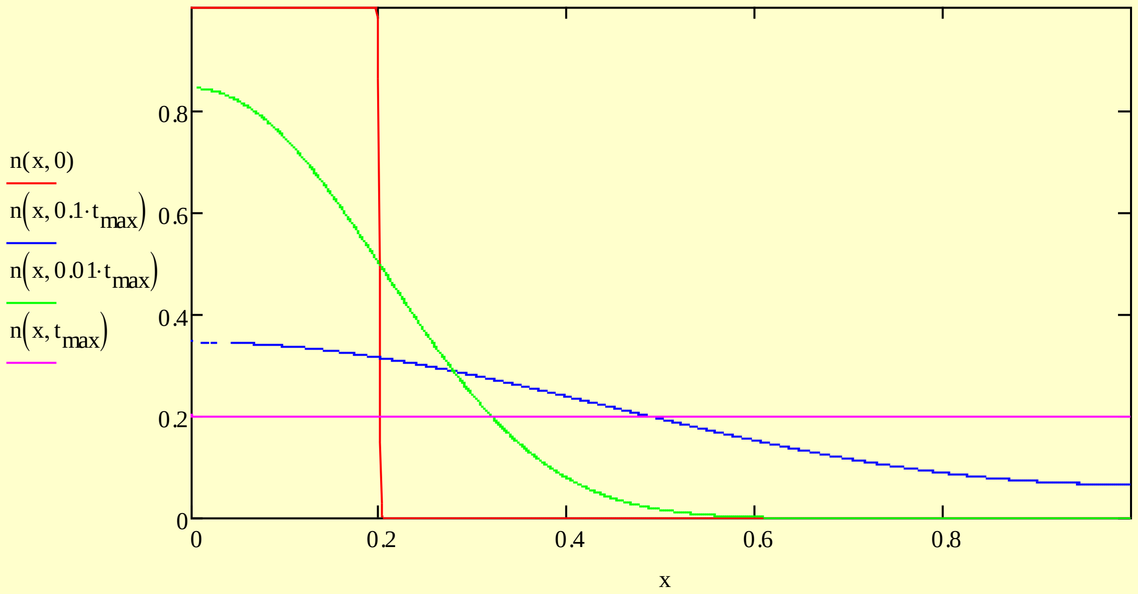
A comparison between the error Function and a linear combination of exponentials – tanh(*x*).

Examples of Profiles at Different Times

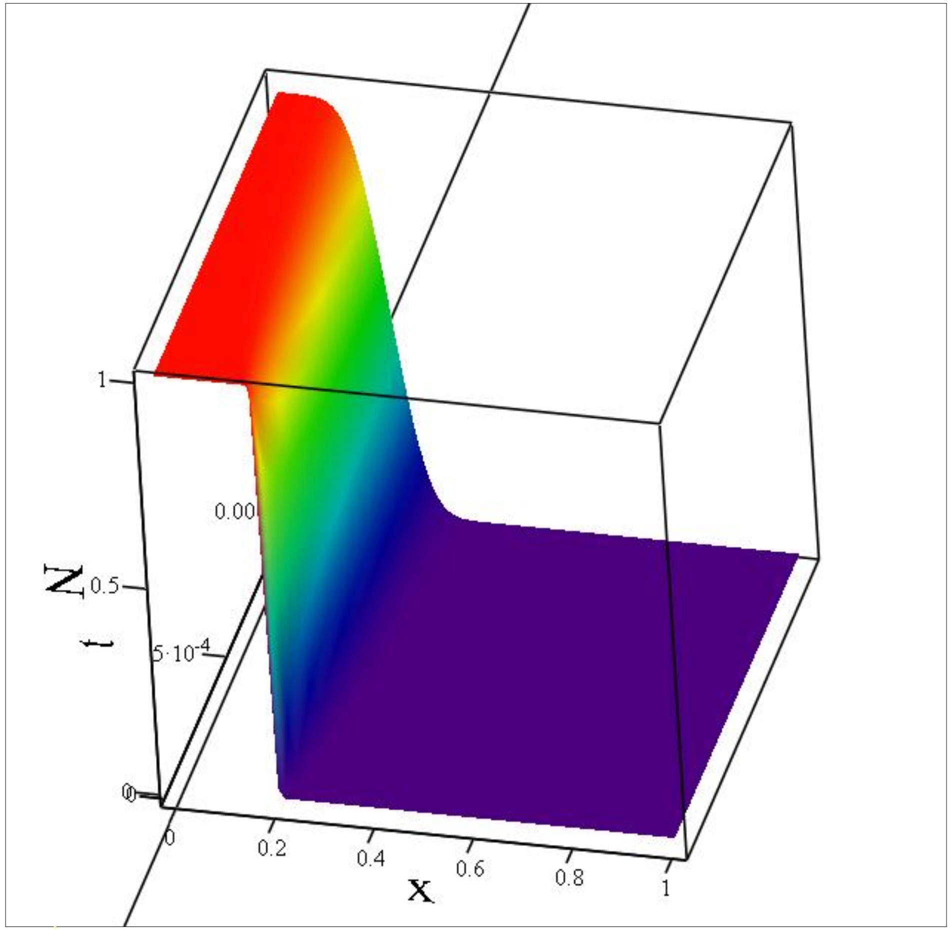
Solve with mixed – Neumann for zero first derivative; Dirichlet for the function as the source must be kept constant.



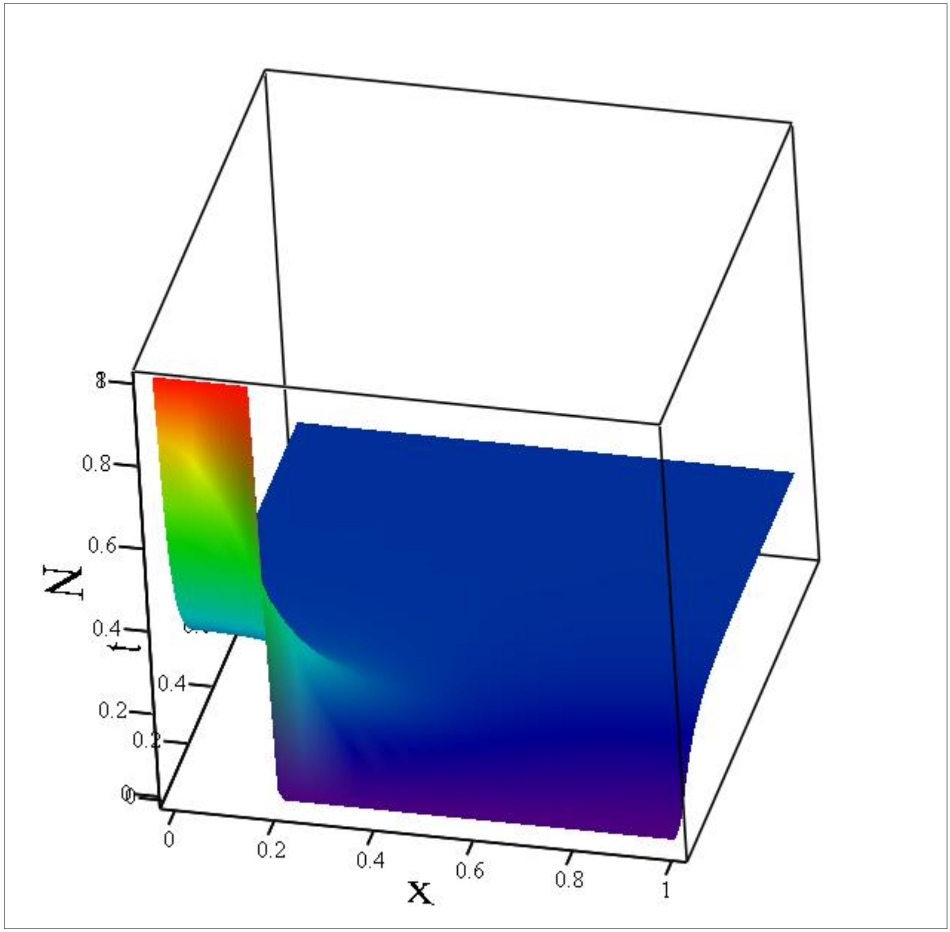
Solve with Neumann boundary conditions at the right border – flat profile – both first and second derivative must be zero.



Direct Comparison of the two Types



Constant Source Diffusion
Sharper profiles for short times.



Finite Source Diffusion
Smoother and deeper profiles.

Thanks and Acknowledgements

Thank You Very Much for Your Attention!