Cleaning

Wafer cleaning is about 30% of all processes.

Particles - brushes, water jets, shockwaves
    cause: lithography defects, pinholes, shorts
Organics - peroxide, O_2 plasma
    hydrophobic (inhibits water cleaning)
    residues keep subsequent layers from sticking
Metals - Acids ($HCl–H_2O_2$ and $H_2SO_4–H_2O_2$)
Oxide - HF

Clean rooms

Filtered air to remove particles
Overpressure maintained to blow dirt out
Controlled temperature and humidity
    Important to make processes reproducible

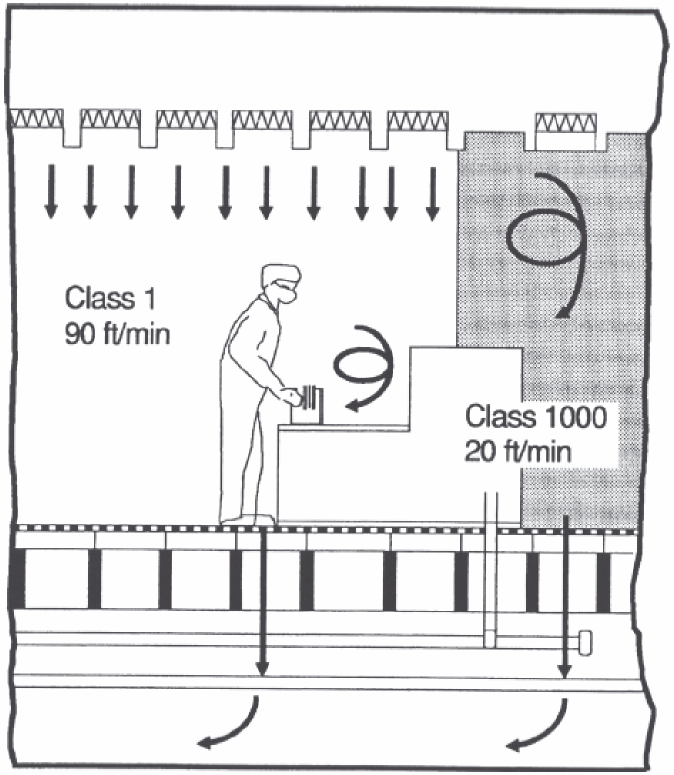

Figure 35.5 Cleanroom and gray area: ISO 3 (Class 1) area for wafer processing, ISO 6 (Class 1000) turbulent flow in service aisle Reproduced from Whyte (2001) by permission of John Wiley & Sons, Ltd

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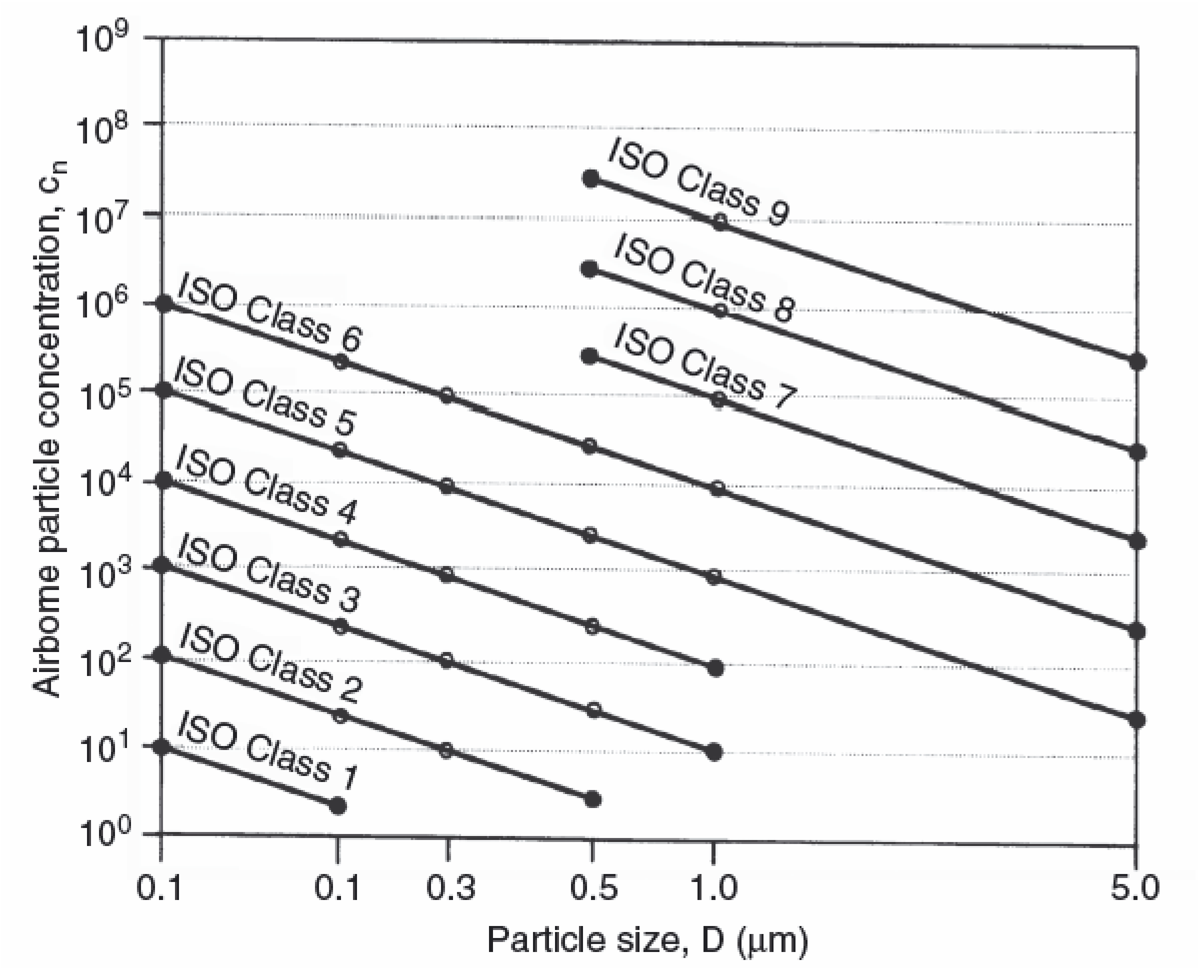
http://www.cleanroominnovation.com

Particles

Flakes from chamber walls
Wear of mechanical parts



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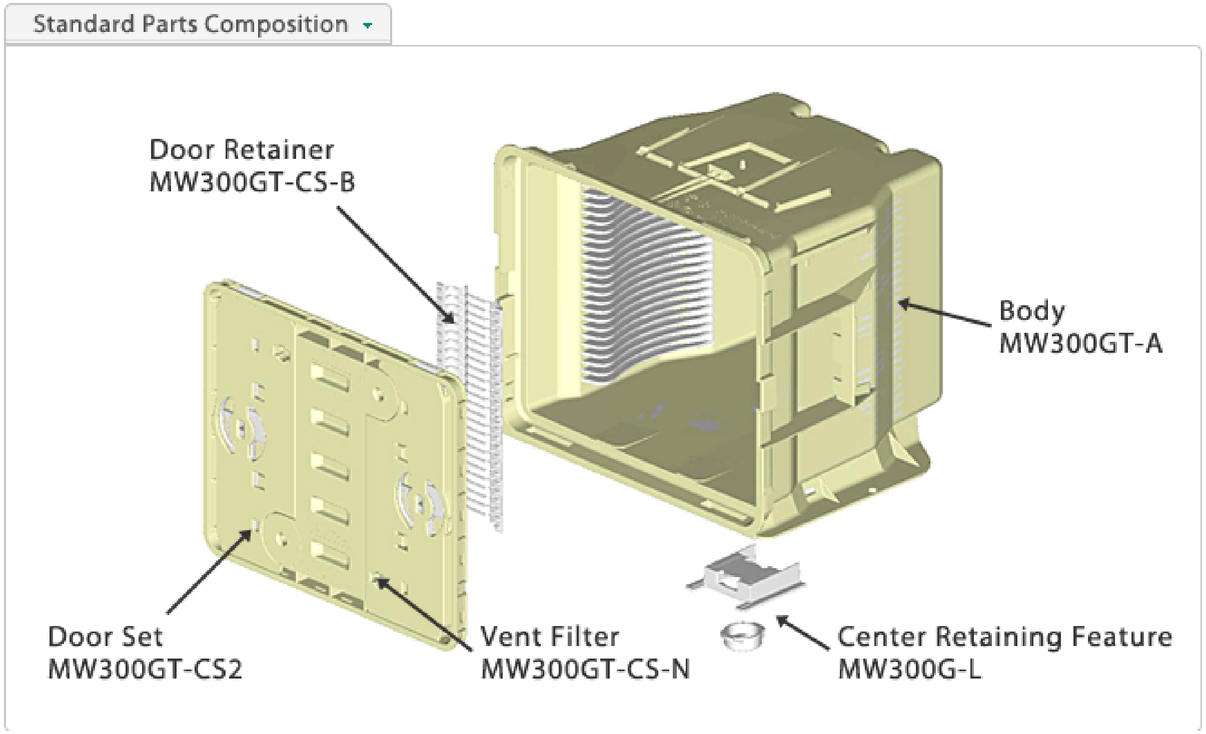
The concentration of particles increases exponentially as their size decreases.

Foup (Front Opening Universal Pod)

- FIMS Door/Automated operation
- Manual open/close function
- Robust structure for perfect seal during transportation
- Design to minimize Cleaning and Drying Cycle Time
- Conforms to SEMI Standard M31

Dimensions : W389 x L340 x H331 (mm)
Weight : 7.5kg(16.9lb) Including 25 wafers
4.3kg(9.7lb) without wafers



https://www.shinpoly.co.jp/business/seimitsu/300gt/index.html

Wafer handling

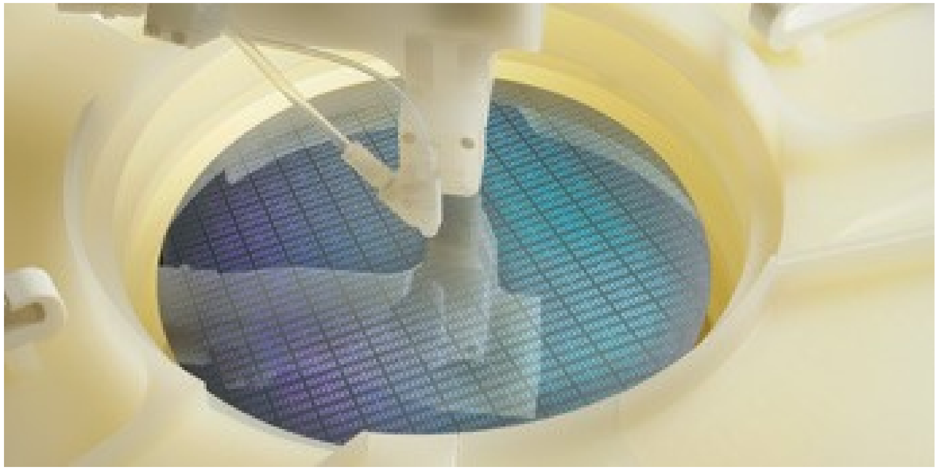
Wafer transport

https://www.youtube.com/watch?v=-KTKg0Y1snQ

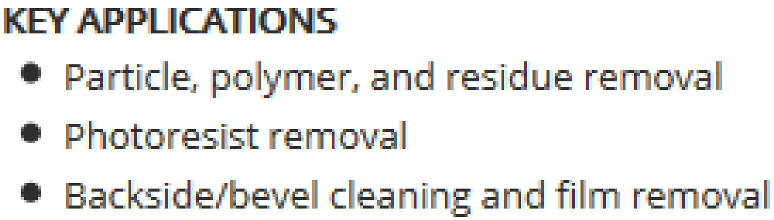
Foup cleaning

Cleaning

Lam RESEARCH



Wafer cleaning is a critical function that must be repeated many times during semiconductor manufacturing.



KEY APPLICATIONS

- Particle, polymer, and residue removal
- Photoresist removal
- Backside/bevel cleaning and film removal

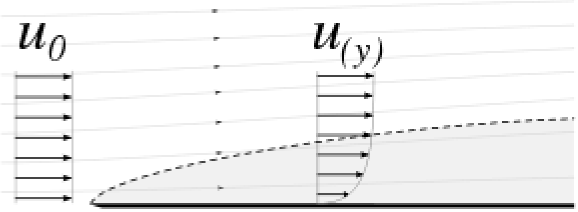
Villach/Austria is the global centre for the development and production of all single-wafer spin technology products for back- and front- end-of-line (BEOL/FEOL) cleaning, etching and stripping applications.

Photoresist strip

Lam
RESEARCH

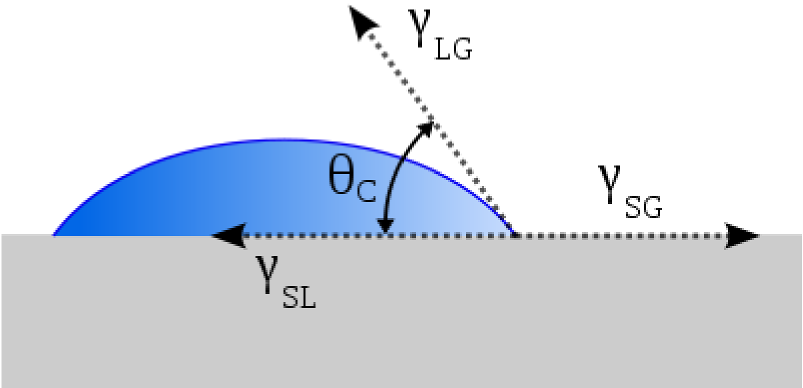
Strip processes remove photoresist material after it has served to "protect" certain areas of the wafer surface from being altered.

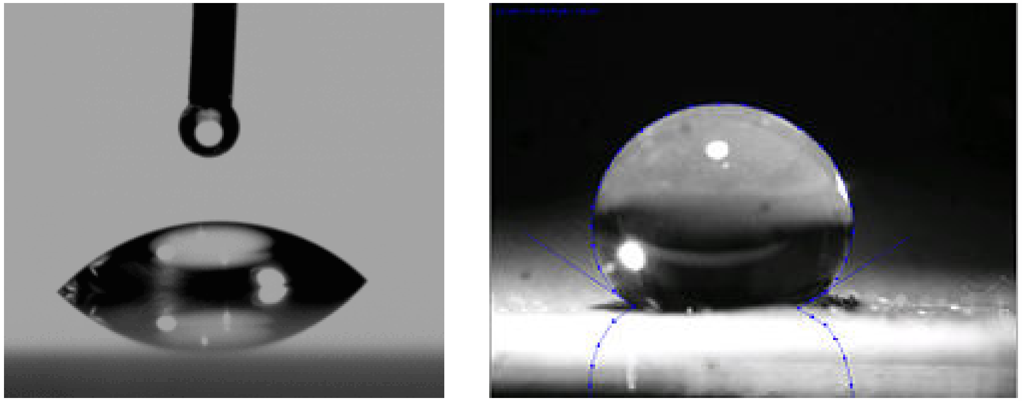
Chemistry and fluid mechanics are important.



http://www.lamresearch.com/products/strip-clean-products

Contact angle





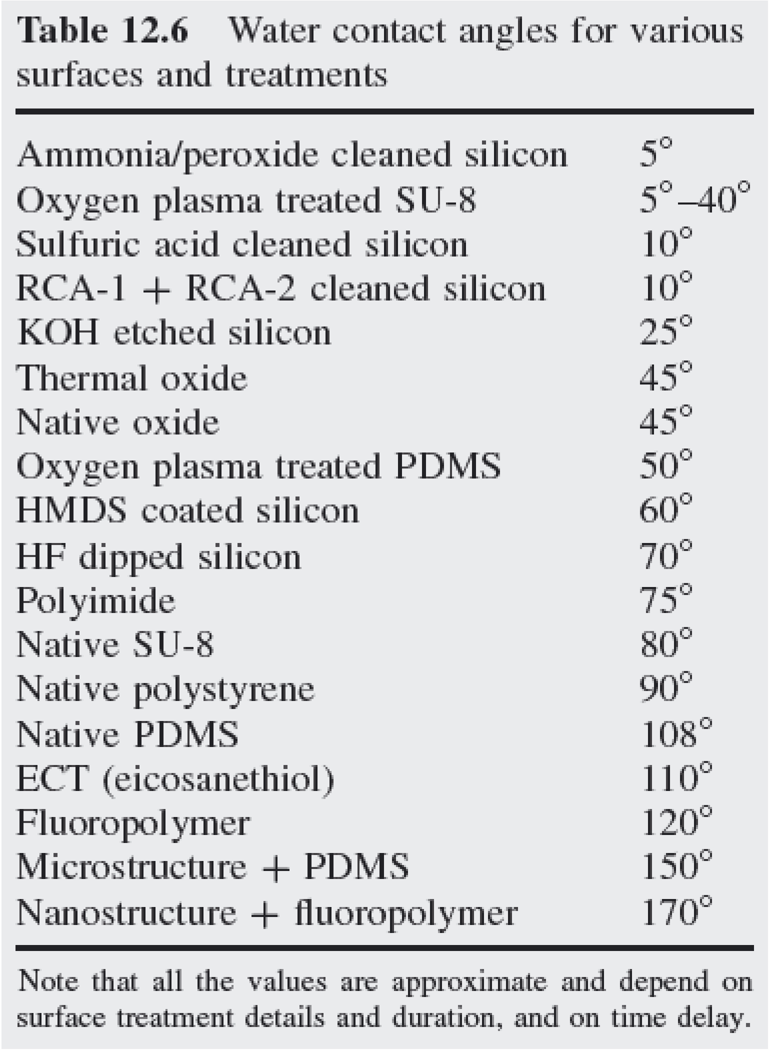


Table 12.6 Water contact angles for various surfaces and treatments

Ammonia/peroxide cleaned silicon	5°
Oxygen plasma treated SU-8	5°–40°
Sulfuric acid cleaned silicon	10°
RCA-1 + RCA-2 cleaned silicon	10°
KOH etched silicon	25°
Thermal oxide	45°
Native oxide	45°
Oxygen plasma treated PDMS	50°
HMDS coated silicon	60°
HF dipped silicon	70°
Polyimide	75°
Native SU-8	80°
Native polystyrene	90°
Native PDMS	108°
ECT (eicosanethiol)	110°
Fluoropolymer	120°
Microstructure + PDMS	150°
Nanostructure + fluoropolymer	170°

Note that all the values are approximate and depend on surface treatment details and duration, and on time delay.

http://en.wikipedia.org/wiki/Contact_angle

Dry cleaning

Etching using plasmas or gases
Can be used in a MBE or CVD chamber
Ozone/UV for organics
HF vapors for oxide
Cl_2 for metals
Ar milling/sputter cleaning for anything

Drying

DI water -> IPA -> Blow dry N_2

Doping

Add donors (n-type) or acceptors (p-type)

- 10^{12} cm^{-3} impurity limit
- 10^{21} cm^{-3} solubility limit

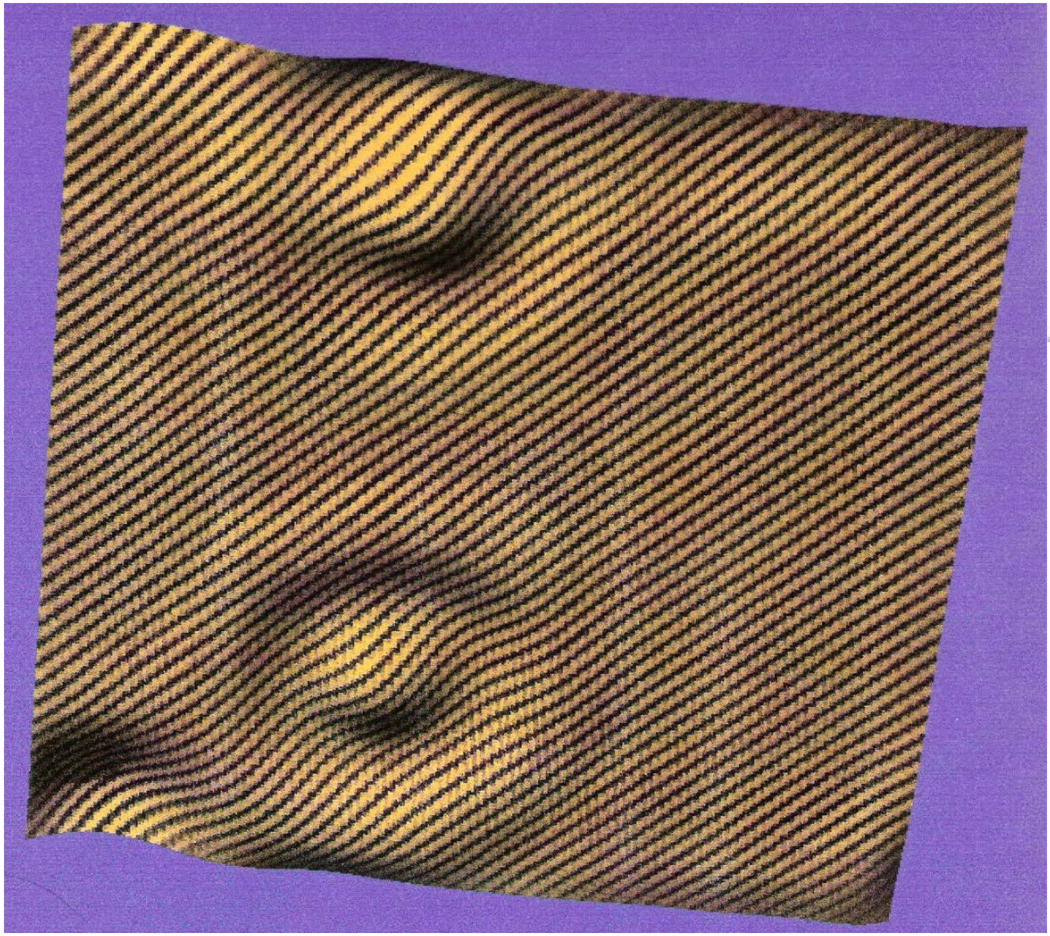
Dopants added

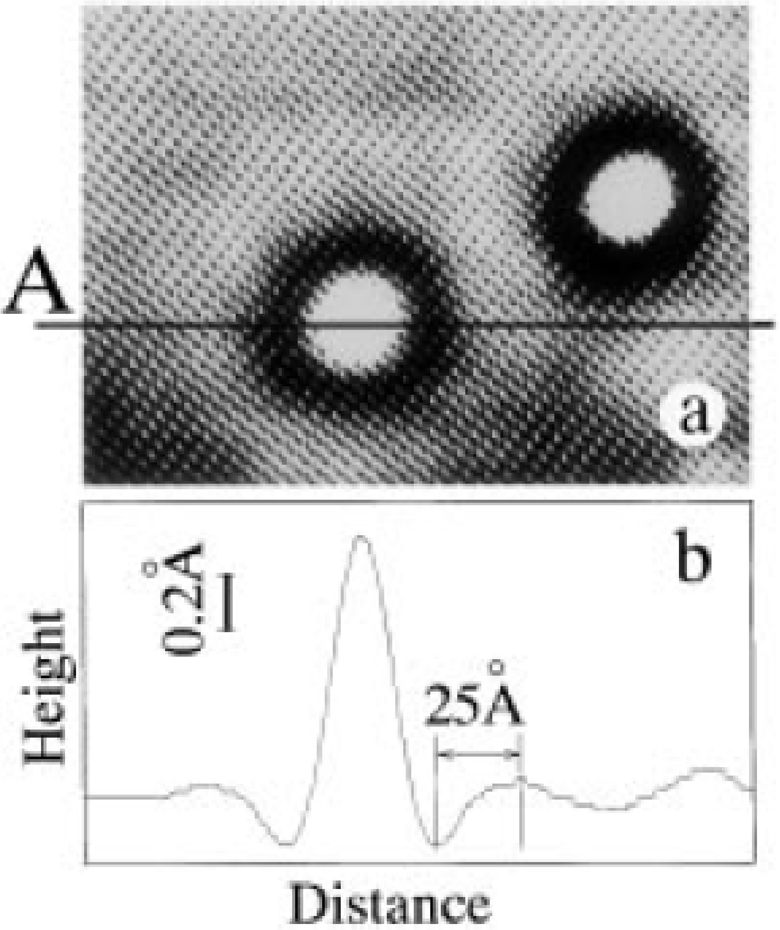
- during crystal growth (whole wafer)
- neutron transmutation (whole wafer)
- during epitaxy (layers)
- diffusion (local)
- ion implantation (local)

Direct Observation of Friedel Oscillations around Incorporated $\mathrm{Si}_{\mathrm{Ga}}$ Dopants in GaAs by Low-Temperature Scanning Tunneling Microscopy

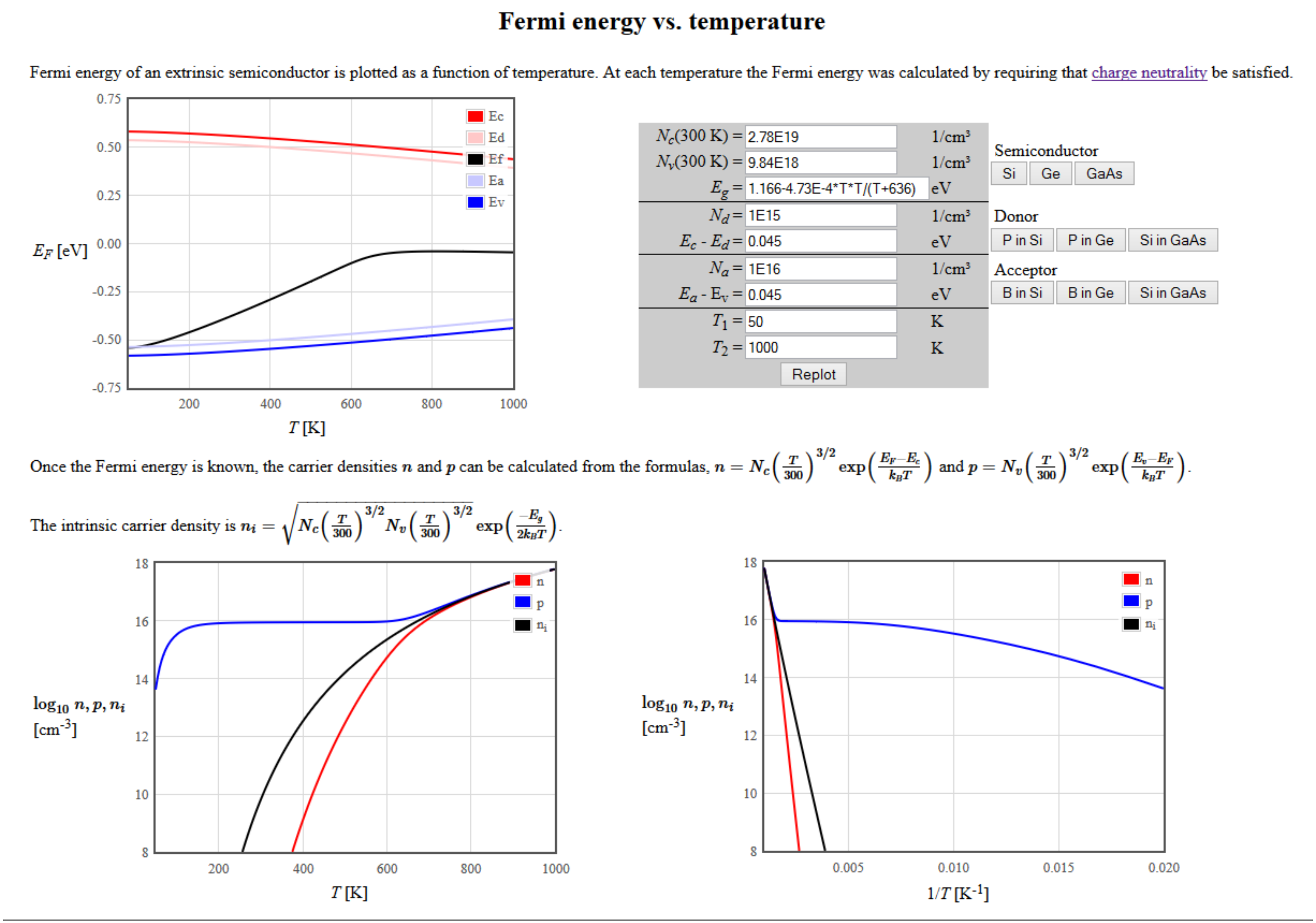
M. C. M. M. van der Wielen, A. J. A. van Roij, and H. van Kempen
Research Institute for Materials, University of Nijmegen, Toernooiveld 1, 6525 ED Nijmegen, The Netherlands

(Received 25 July 1995)





Doping determines the carrier concentration



Fermi energy vs. temperature

Fermi energy of an extrinsic semiconductor is plotted as a function of temperature. At each temperature the Fermi energy was calculated by requiring that charge neutrality be satisfied.

N_c(300 K) = 2.78E19 1/cm³
N_v(300 K) = 9.84E18 1/cm³
E_g = 1.166-4.73E-4*T*T/(T+636) eV
N_d = 1E15 1/cm³
E_c - E_d = 0.045 eV
N_a = 1E16 1/cm³
E_a - E_v = 0.045 eV
T_1 = 50 K
T_2 = 1000 K
Replot

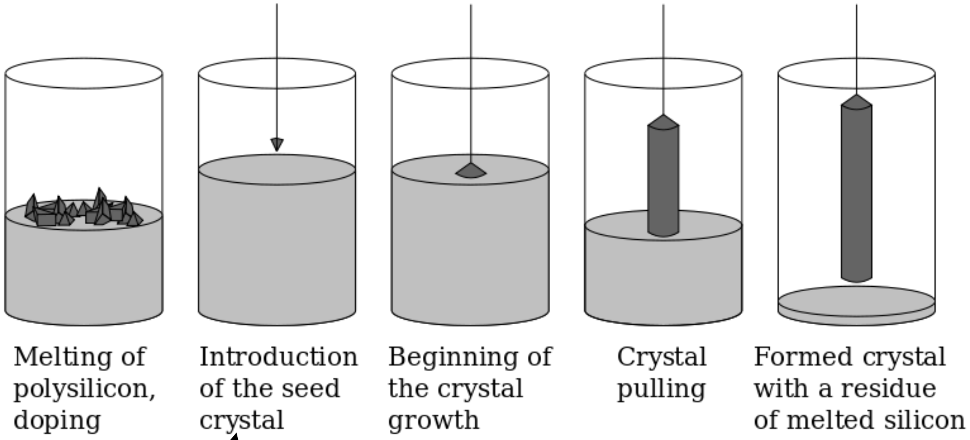
Once the Fermi energy is known, the carrier densities n and p can be calculated from the formulas, $n = N_c\left(\frac{T}{300}\right)^{3/2}\exp\left(\frac{E_F - E_c}{k_BT}\right)$ and $p = N_v\left(\frac{T}{300}\right)^{3/2}\exp\left(\frac{E_v - E_F}{k_BT}\right)$.

The intrinsic carrier density is $n_i = \sqrt{N_c\left(\frac{T}{300}\right)^{3/2} N_v\left(\frac{T}{300}\right)^{3/2}\exp\left(\frac{-E_g}{2k_BT}\right)}$.

http://lamp.tu-graz.ac.at/~hadley/psd/L4/eftplot.html

Crystal growth

Czochralski Process



add dopants to the melt

images from wikipedia

Crystal growth

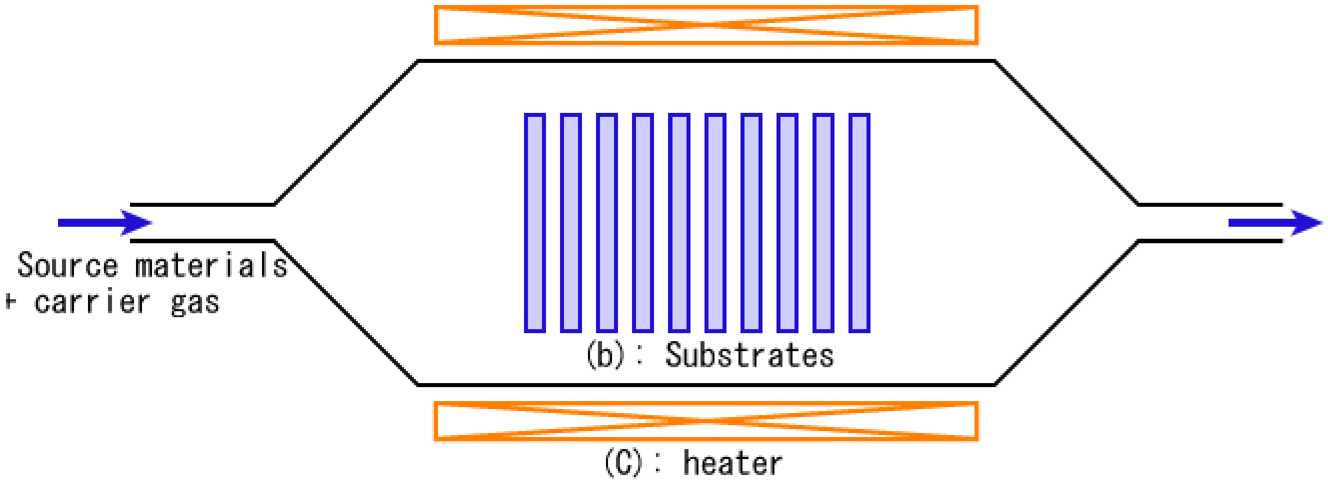
Float zone Process

image from wikipedia

Neutron transmutation

$^{30}\text{Si} + n \rightarrow \; ^{31}\text{Si} + \gamma$
$^{31}\text{Si} \rightarrow \; ^{31}\text{P} + \beta$

Chemical vapor deposition



Epitaxial silicon CVD SiH_4 (silane) or SiH_2Cl_2 (dichlorosilane)
PH_3 (phosphine) for n-doping or B_2H_6 (diborane) for p-doping.

The doping can be adjusted in layers.

image from wikipedia

Gas phase diffusion

AsH_3 (Arsine) or PH_3 (phosphine) for n-doping
B_2H_6 (diborane) for p-doping.
100 - 200 wafers in a batch.

http://www.microfab.de/foundry/services/diffusion/index.html

Gas phase diffusion

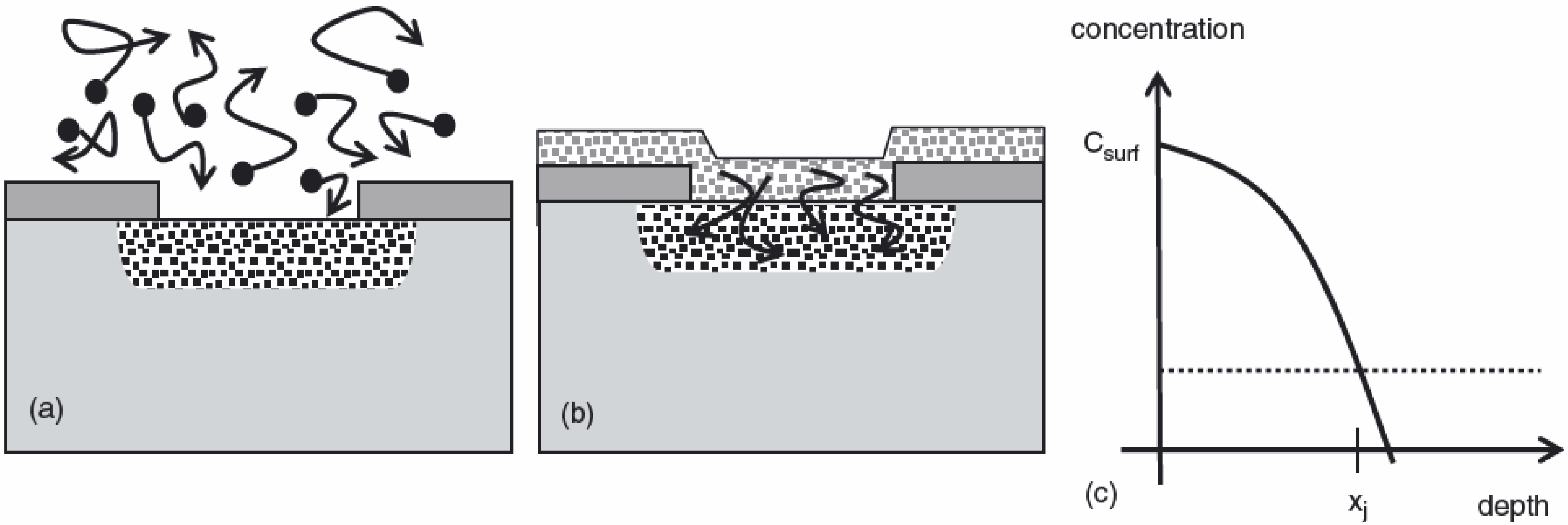


Figure 14.1 Thermal diffusion: (a) gas phase diffusion with oxide mask; (b) diffusion from doped thin film with oxide mask; (c) dopant profile and junction depth x_j

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900 – 1200 C
1000 C for 1 hour ~ 1 µm

Constant Source Diffusion

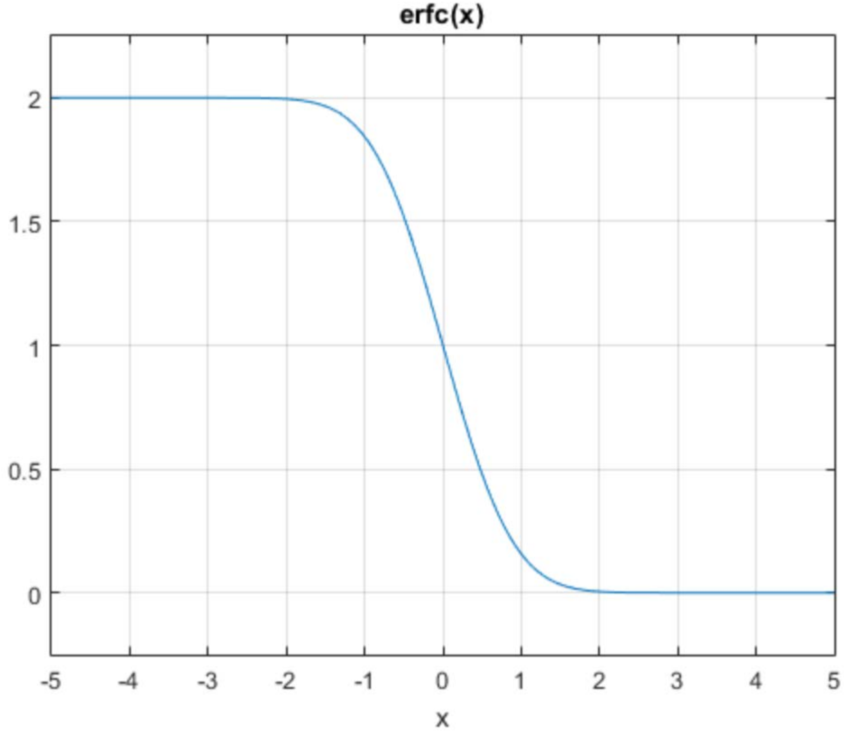
$$\frac{dC}{dt} = -D\nabla^2 C$$

Diffusion equation

For a constant source concentration C_0 at the surface:

$$C(z) = C_0 \operatorname{erfc}\left(\frac{z}{2\sqrt{Dt}}\right)$$

$$\operatorname{erfc}(x) = 1 - \frac{2}{\sqrt{\pi}}\int_0^x e^{-t^2}\,dt$$



The concentration decreases about linearly

$$\operatorname{erfc}(z) = 1 - \frac{2z}{\sqrt{\pi}} + \cdots$$

Constant source diffusion

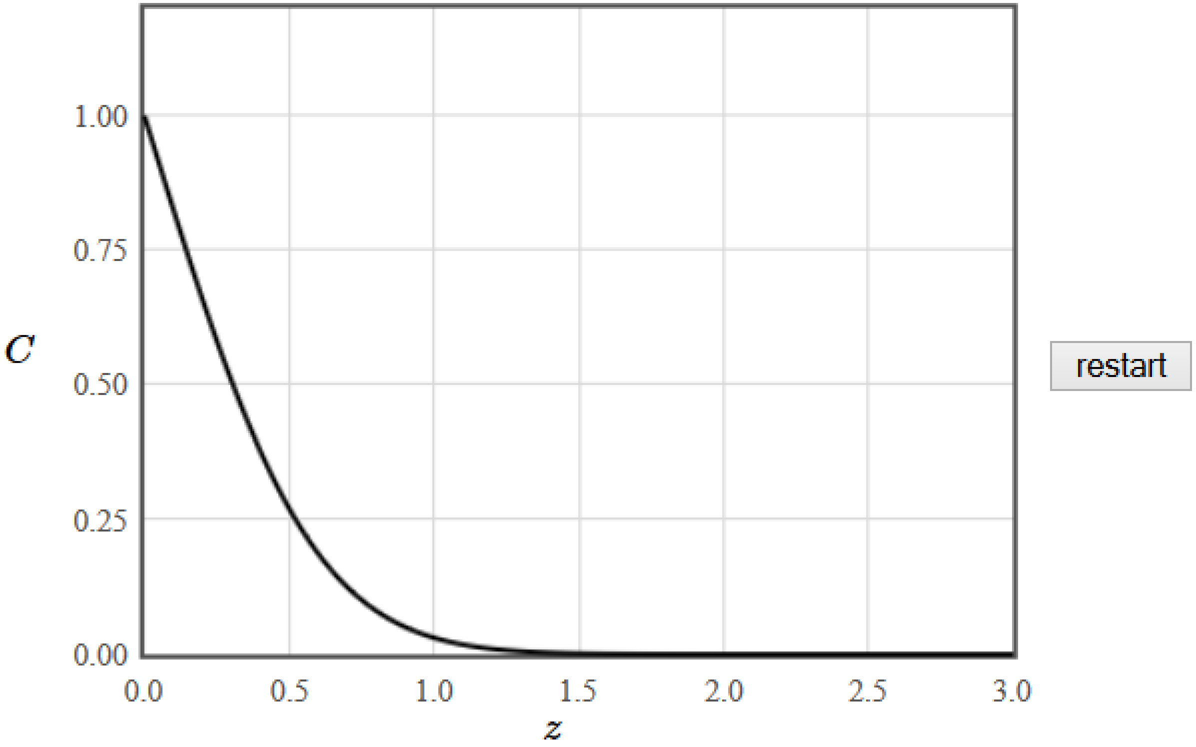
The diffusion equation is,

$$\frac{\partial C}{\partial t} = D\nabla^2 C\,.$$

In constant source diffusion, the concentration is held constant at the surface. The concentration of dopants is,

$$C(z,t) = C_0 \operatorname{erfc}\left(\frac{z}{\sqrt{4Dt}}\right).$$

The concentration falls at the surface and the total number of dopants remains constant.

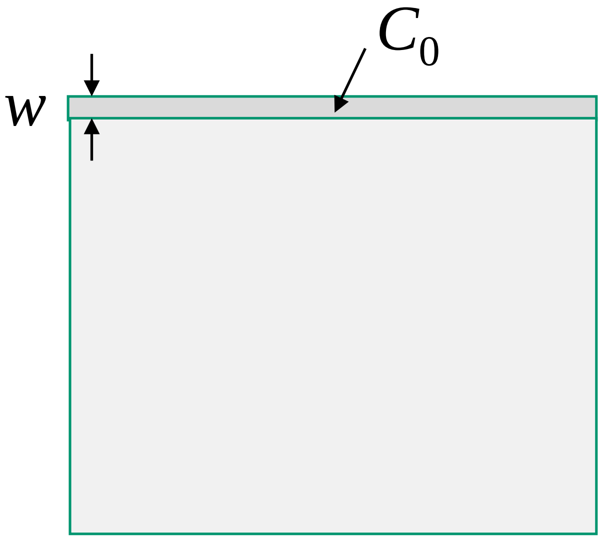


Limited Source Diffusion

$$\frac{dC}{dt} = -D\nabla^2 C$$

Diffusion equation

For a limited source concentration C_0 at the surface:



$$C(z) = \frac{C_0 w}{\sqrt{4\pi Dt}} \exp\left(-\frac{z^2}{4Dt} \right)$$

$$C(z) = \frac{C_0 w}{\sqrt{4\pi Dt}} \left(1 - \frac{z^2}{4Dt} + \cdots \right)$$

Limited source diffusion

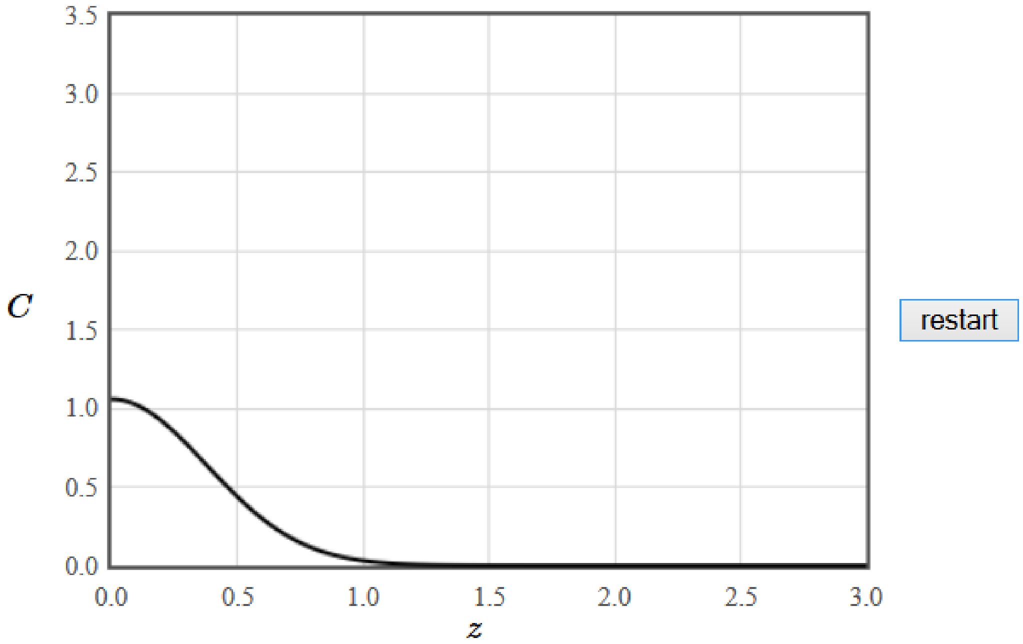
The diffusion equation is,

$$\frac{\partial C}{\partial t} = D\nabla^2 C\,.$$

If a limited source of dopants is deposited in a thin layer with a thickness w at the surface such that the dose Q in dopants per square meter is $Q = \int\limits_0^w dz$, the concentration as a function of time

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

The concentration falls at the surface and the total number of dopants remains constant.



Diffusion is thermally activated

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

$$L = \sqrt{4D_0 \exp\left(\frac{-E_A}{k_B T}\right)t}$$ Diffusion length

For P diffusion, 1 h, at 1200 $T = 1473$ K

$L = 1.3$ μm

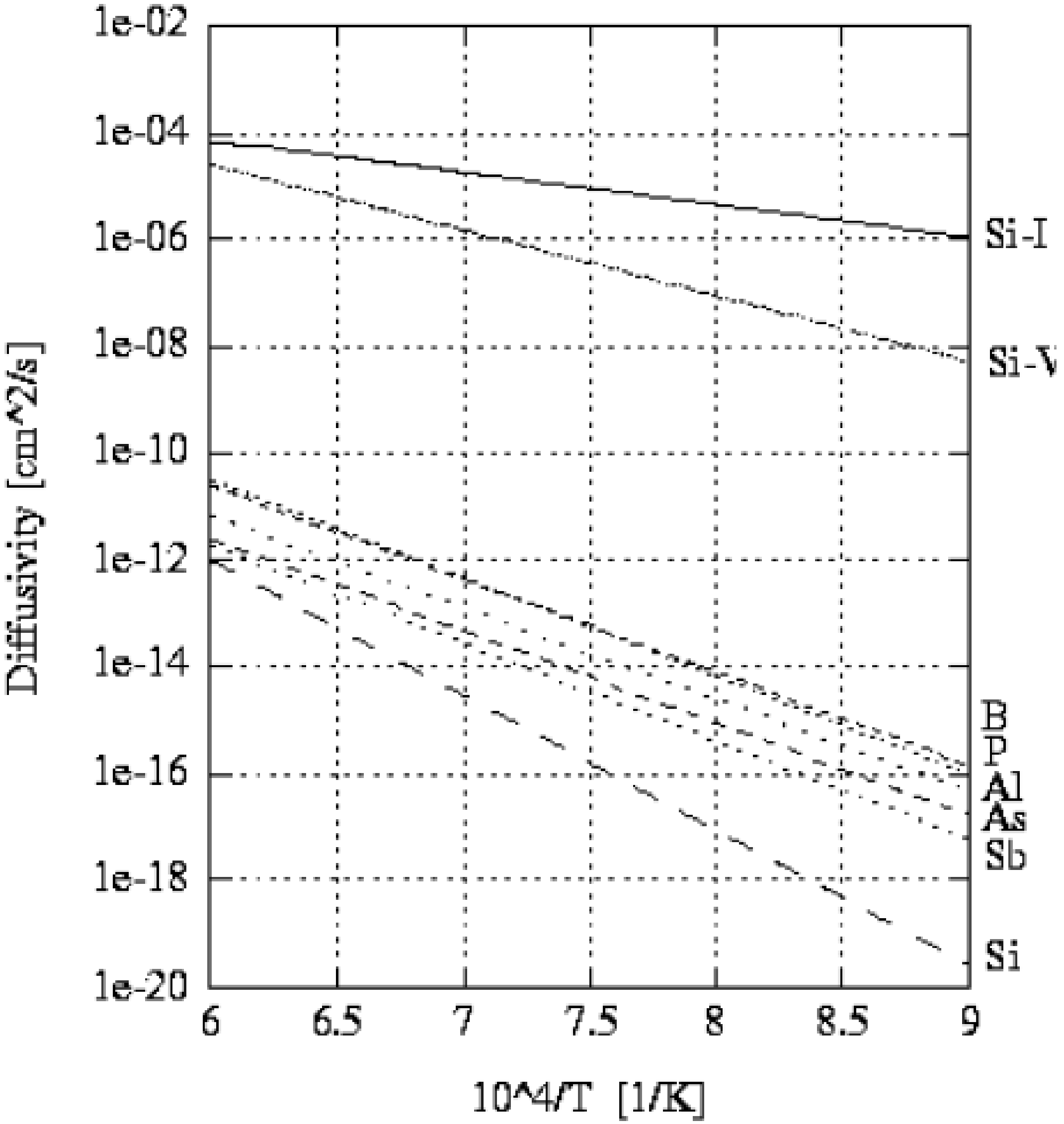
	Si	B	In	As	Sb	P	Units
D_0	560	1.0	1.2	9.17	4.58	4.70	$\mathrm{cm^2\ sec^{-1}}$
E_A	4.76	3.5	3.5	3.99	3.88	3.68	eV

Diffusion

Interstitials and vacancies diffuse quickly and assist the dopants.

BH_3 diffuses faster than B.

Diffusion depends on doping concentration.



Solid solubility limits

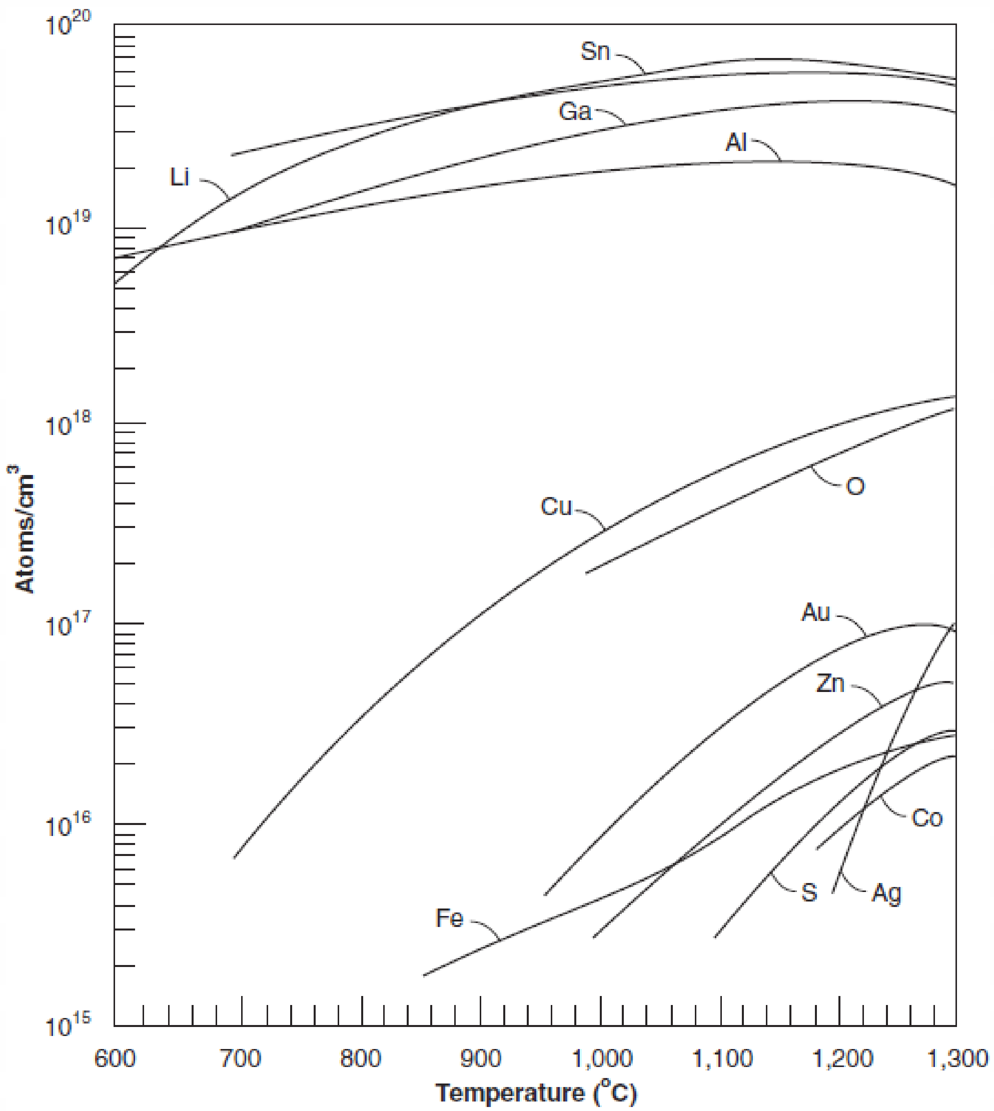
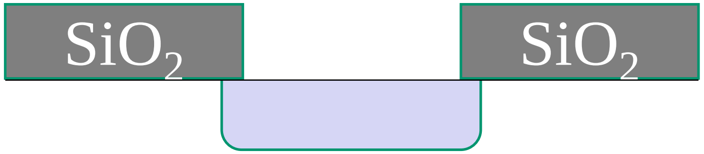


Figure 1.28: Solid solubility of selected impurities in silicon [47].

www-eng.lbl.gov/~shuman/NEXT/.../**Diffusion**in%20**silicon**pdf.pdf

Predeposition/Drive-in

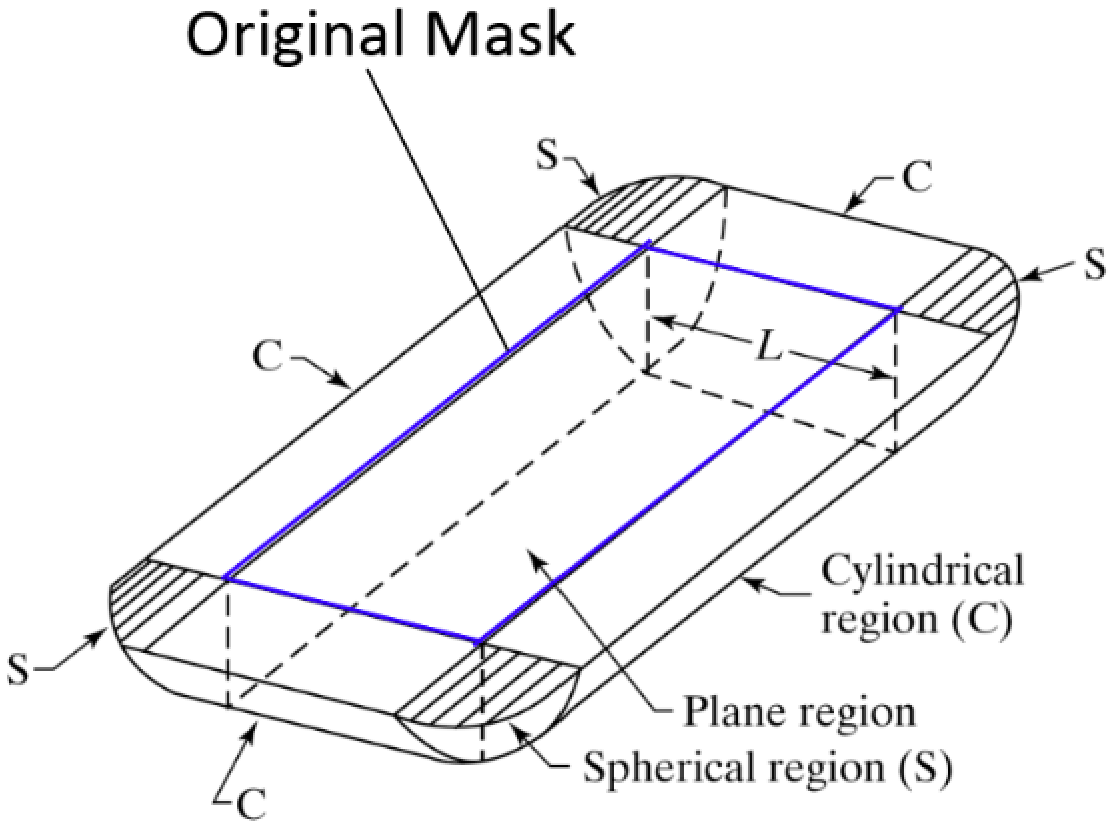
Oxide diffusion mask ~ 500 nm



Predeposition process
- spin-on glass
- ion implantation
- constant source diffusion

Drive-in process
- limited source diffusion

Patterned dopant regions



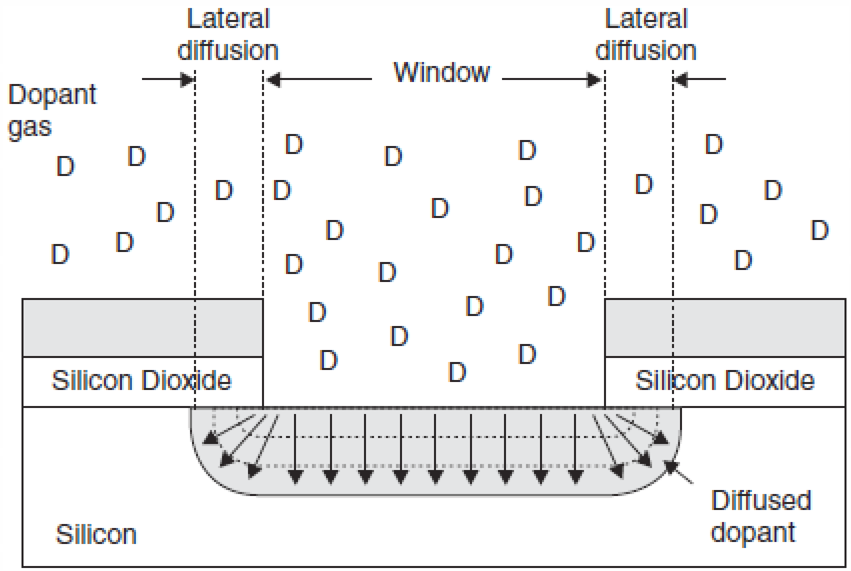
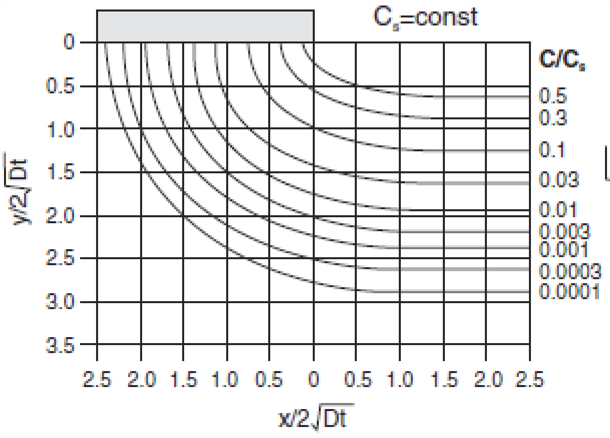
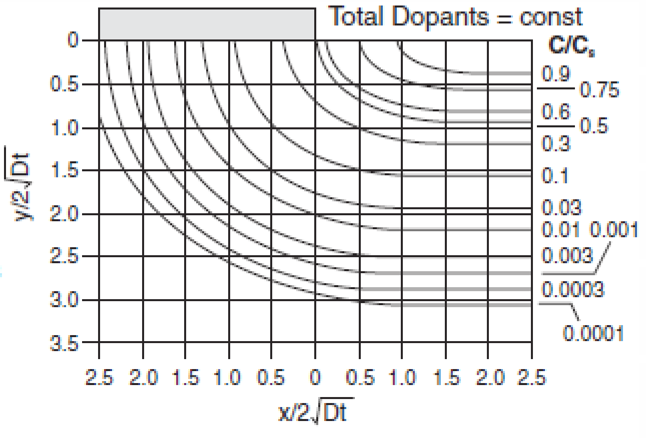


Figure 1.34: Pre-deposition through a silicon dioxide window.



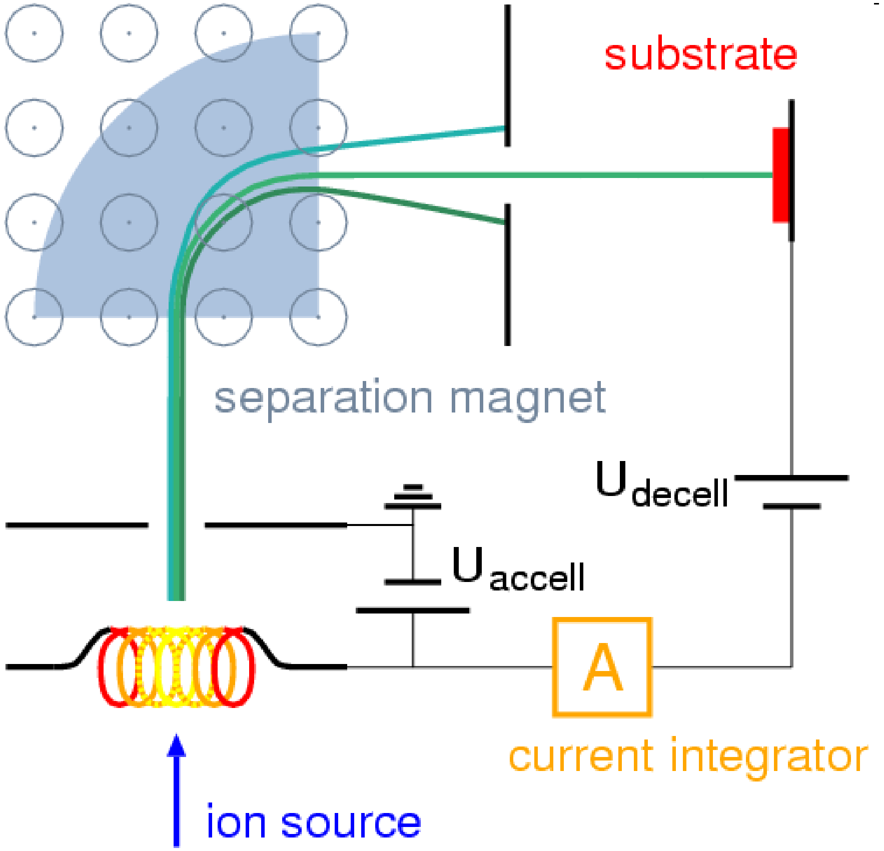
a) Complementary error function



b) Gaussian

www-eng.lbl.gov/~shuman/NEXT/…/**Diffusion**in%20**silicon**pdf.pdf

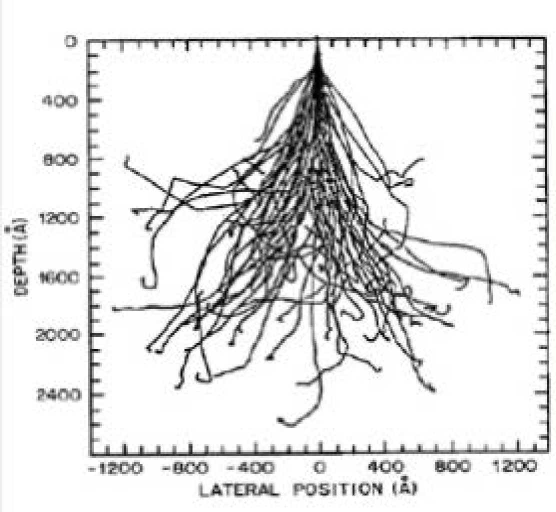
Ion implantation



X-rays are generated

Ion implantation

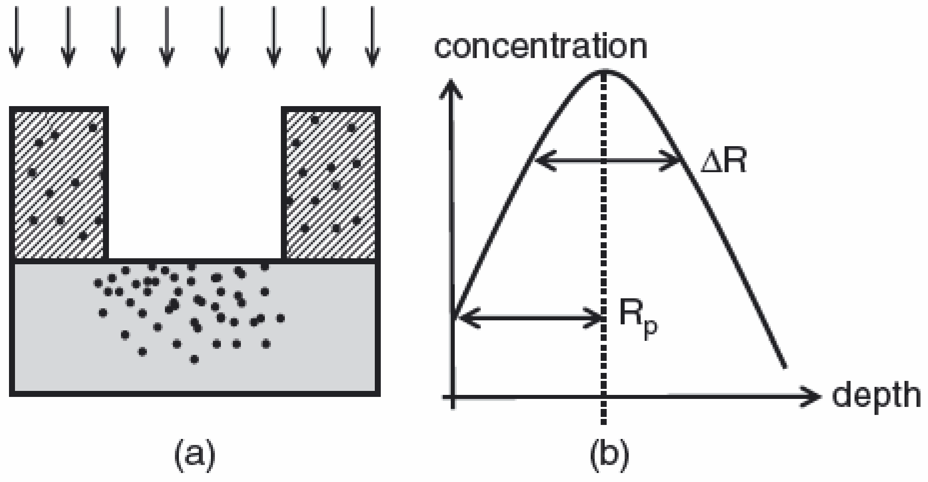
More accurate control of concentration
Better lateral confinement
Low temperature
Complex profiles through multiple implantations
Less sensitive to surface preparation
Requires an anneal to eliminate damage and activate dopants
Dopants diffuse during the anneal
Possible to implant above the solubility limit



http://slideplayer.com/slide/2412041/

Ion implantation

Photoresist, oxide, or nitride. Should be thicker than projected range. High doses burn the photoresist on and make it hard to remove.

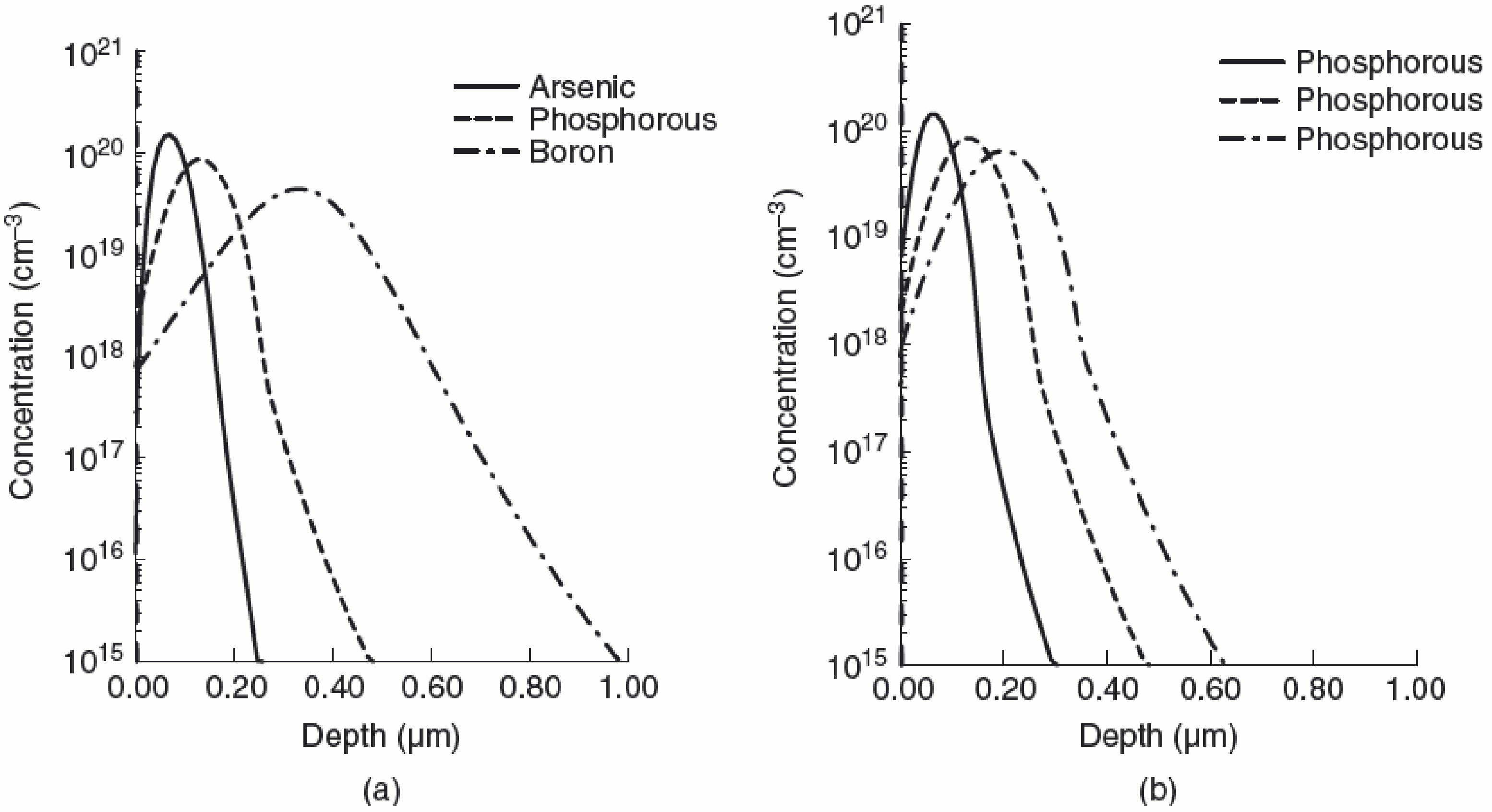


(a) (b)

Figure 15.1 (a) Implantation: mask layer blocks selected areas; (b) dopant concentration profile inside silicon, with projected range R_p and straggle ΔR

Most dopants are at the projected range R_p.

Ion implantation



(a)

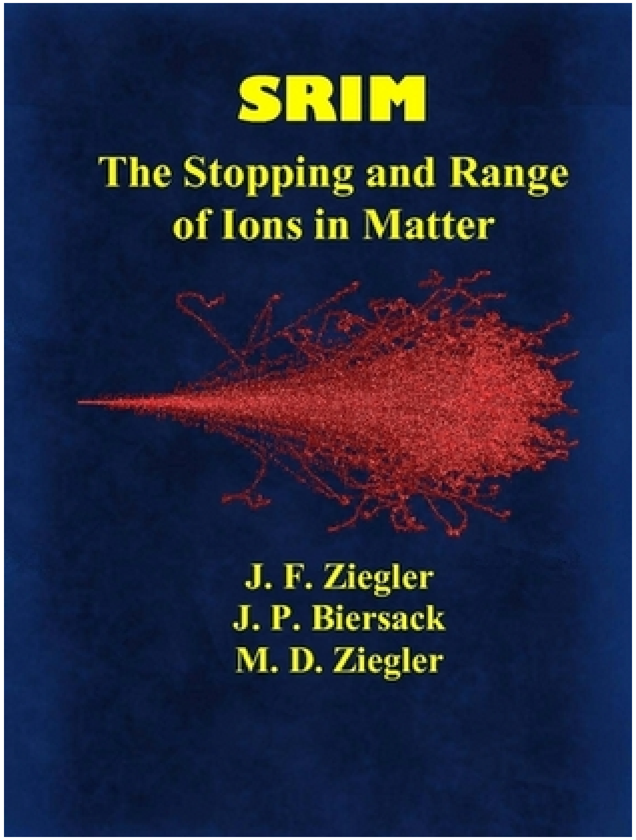
(b)

Figure 15.3 (a) The 50 keV implantation of arsenic, phosphorus and boron: the lighter ions will penetrate deeper. (b) Phosphorus implantation with 50, 100 and 150 keV energies

SRIM

The Stopping and Range of Ions in Matter

James F. Ziegler, Jochen P. Biersack, Matthias D. Ziegler

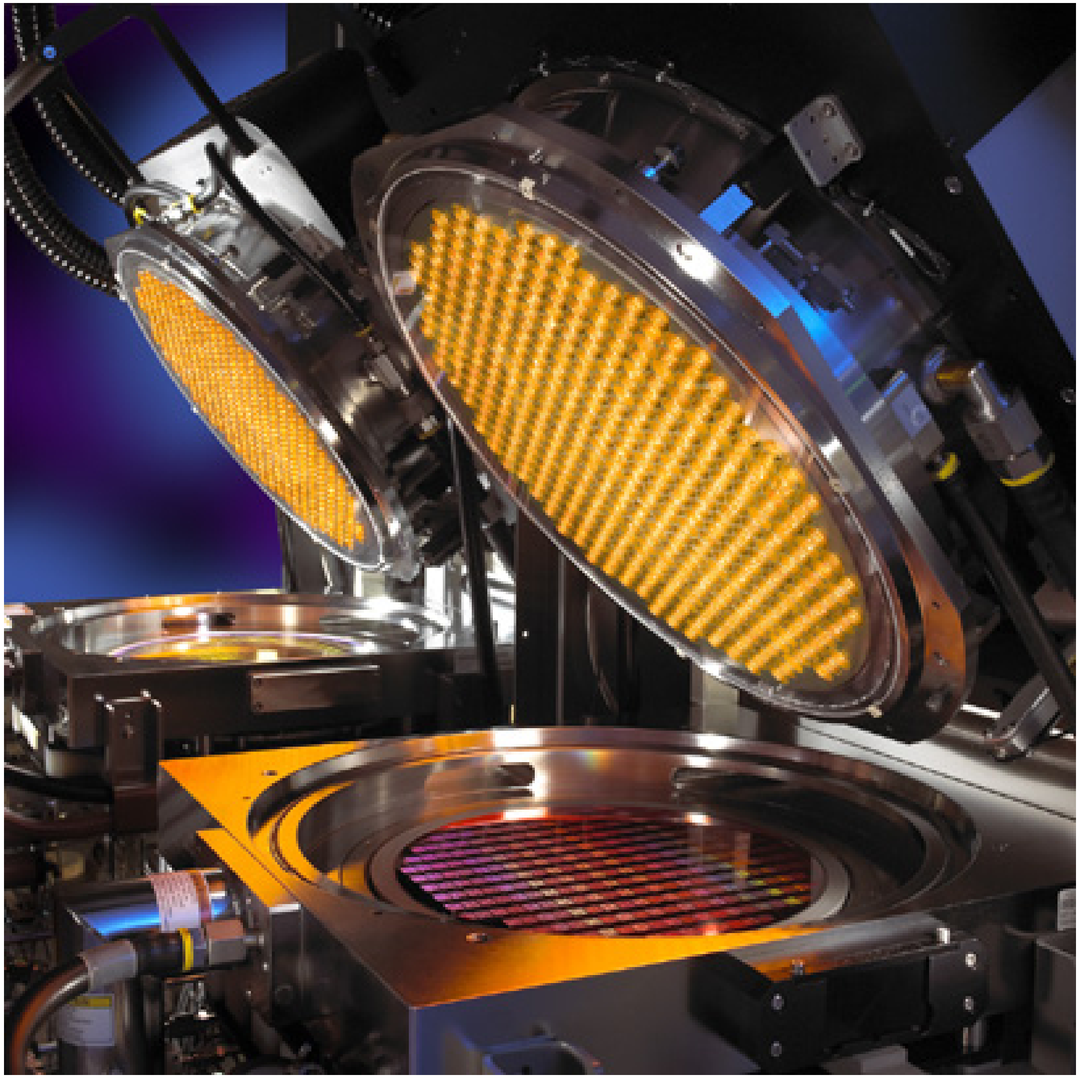


SRIM

The Stopping and Range of Ions in Matter

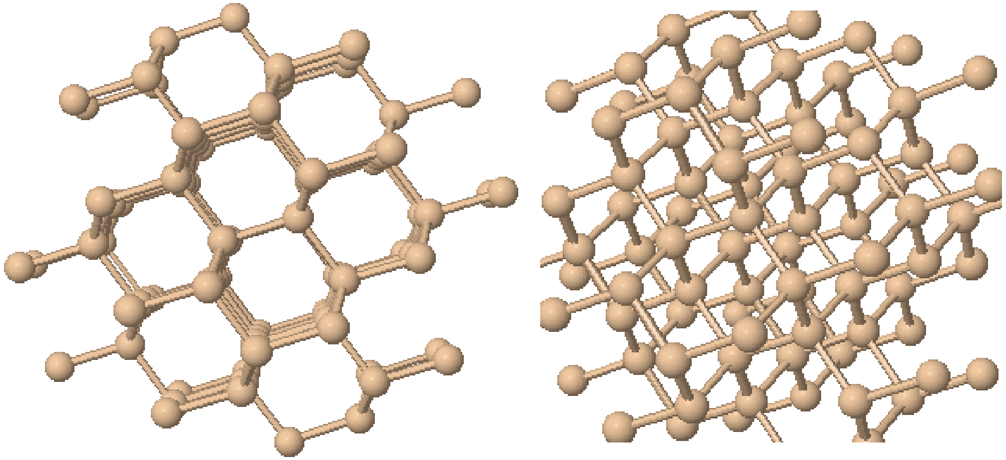
J. F. Ziegler
J. P. Biersack
M. D. Ziegler

Rapid thermal anneal (RTA)



http://www.appliedmaterials.com/products/vantage-radianceplus-rtp

Channeling



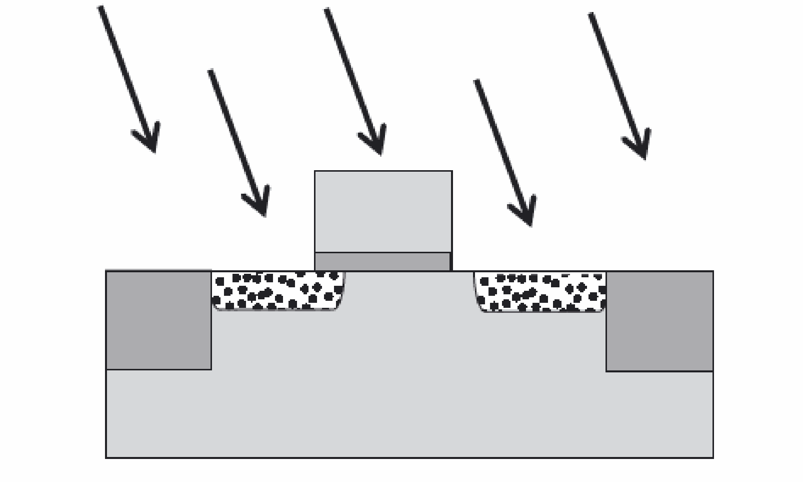


Figure 15.6 Doping asymmetry due to tilted implantation

Ions travel deep into the crystal when the beam is aligned with a crystal axis. Implantation is often done at 7_{o} off-axis to avoid channeling.

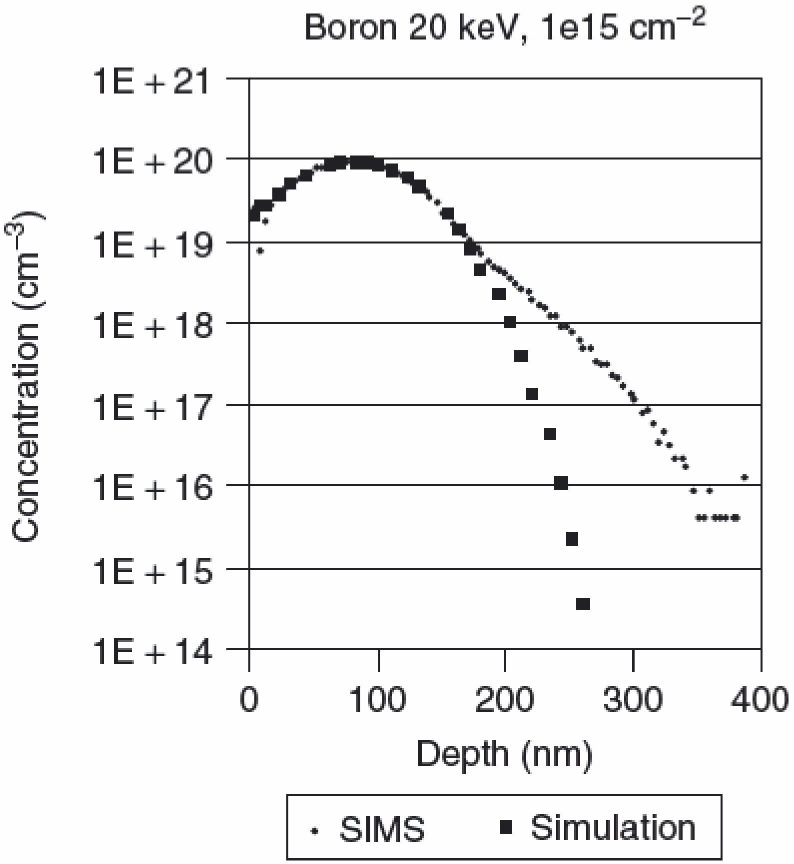
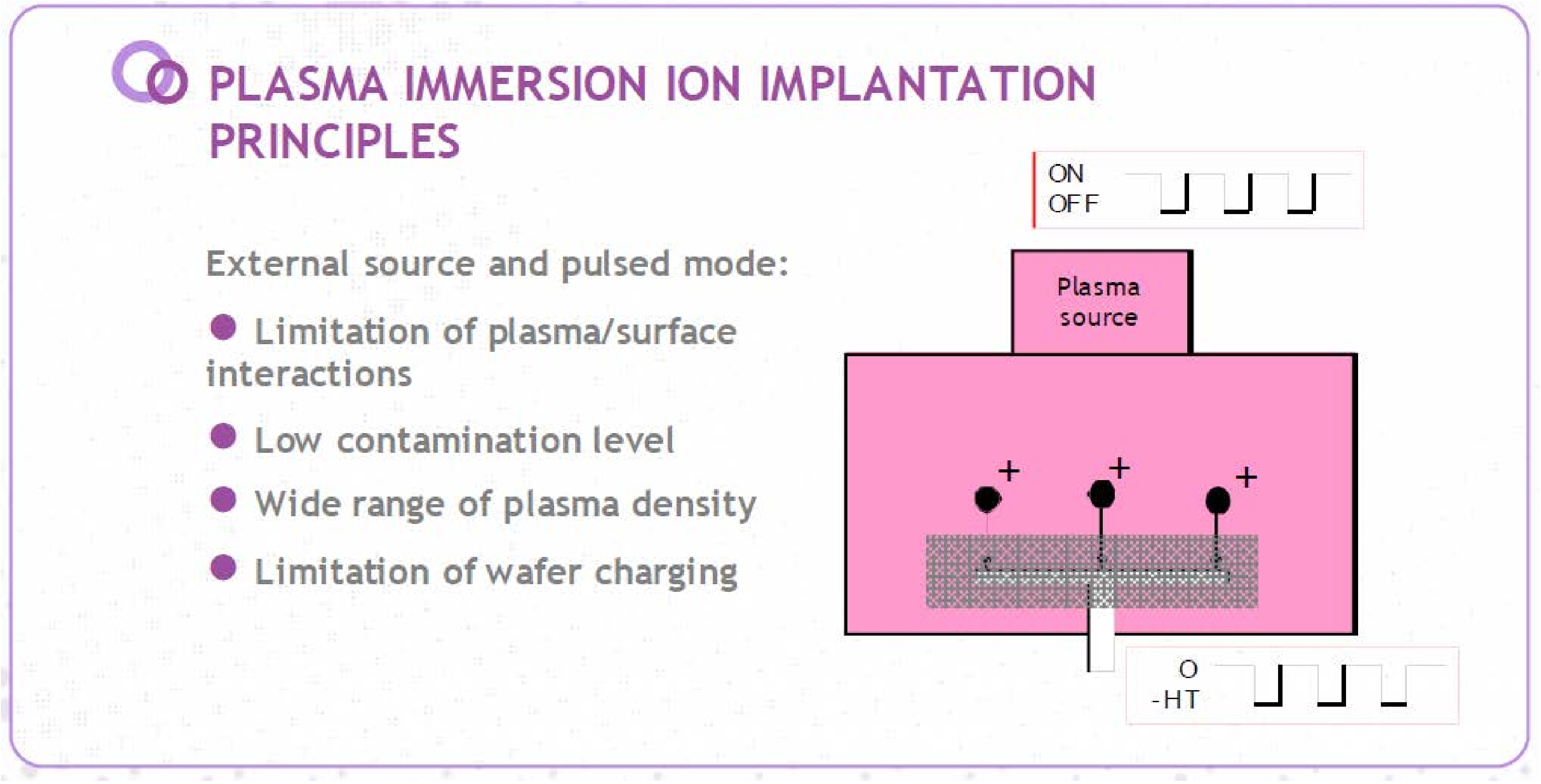


Figure 15.9 Boron implantation into silicon, 20 keV, 10^{15} cm^{-2}. SIMS measured data shown by small diamonds, ICECREM simulation by large squares. The discrepancy in the tail results partly from ion channeling and partly from model deficiencies. SIMS data courtesy Jari Likonen, VTT

Plasma immersion ion implantation



PLASMA IMMERSION ION IMPLANTATION PRINCIPLES

External source and pulsed mode:

- Limitation of plasma/surface interactions
- Low contamination level
- Wide range of plasma density
- Limitation of wafer charging

Flat panel displays and solar panels.

http://www.ion-beam-services.com/services2.htm