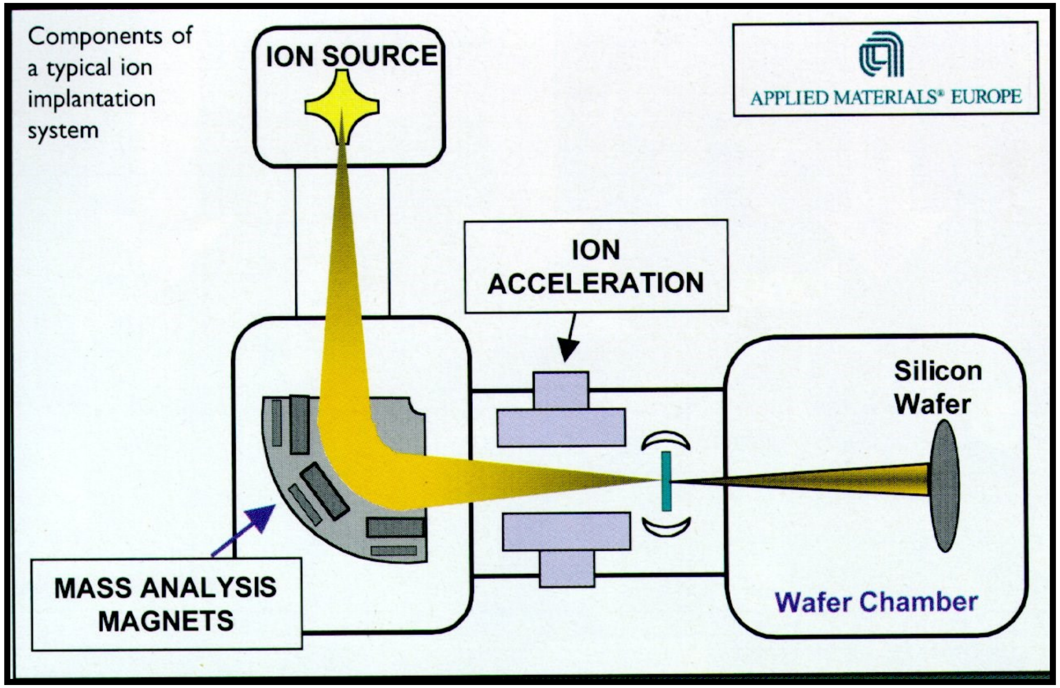
Status: 1.5.2019

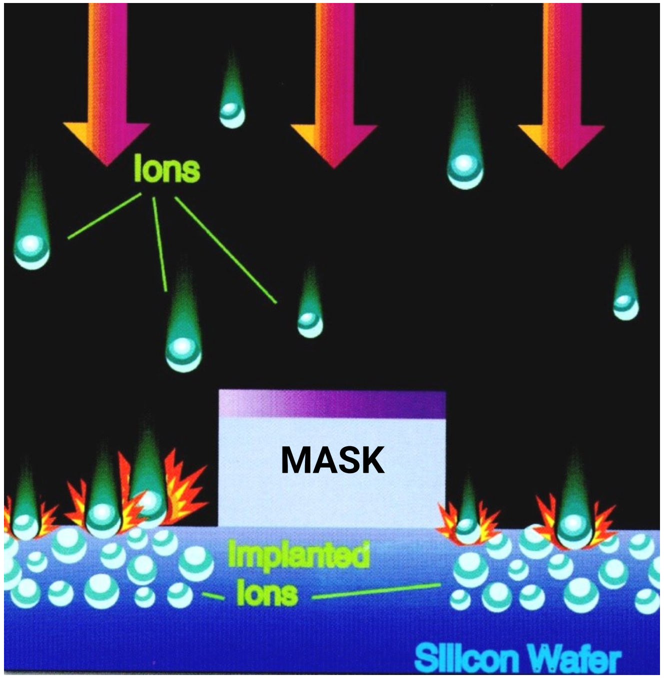
3.5 Ion Implanation

Status: 1.5.2019

3.5.1 Introduction

- Ion implantation comprises ionization of atoms or molecules, separation of the desired kind of ions, acceleration of these ions by an electric field into a solid target, thereby changing the physical, chemical, or electrical properties of the target.
- The distribution of ions in the solid depends on energy, mass, dose, and direction of ions, as well as atomic mass and structure of substrate and cover layers.
- Energy range: keV ... MeV (typical values in Si technology: 5 ... 300 keV)





Goals of Ion Implantation

- **doping**
- modification of material properties
  - amorphization
  - ion beam mixing
  - modification of molecular structure and composition of resist layers (ion beam lithography, resist hardening)
  - hillock suppression for Al interconnects
- stoichiometric implantation , e.g. of O^+, N+ und Si+ for generation of SiO_2, Si_3N_4, and silicide layers both at interfaces and as buried layers in the substrate

Characteristics of Doping by Ion Implantation

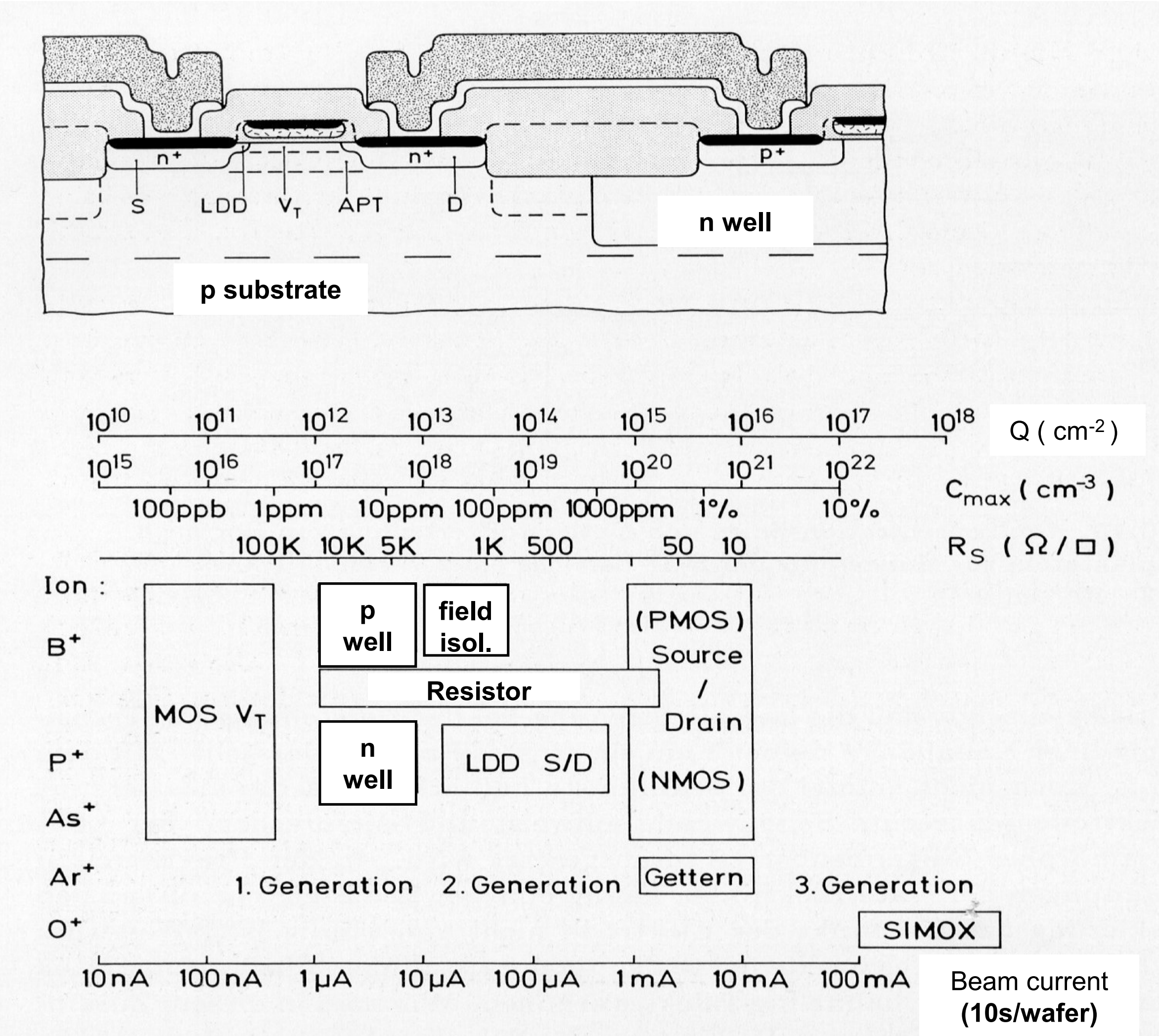
- large doping range
- high precision of dose and energy
- selective implantation using mask layers (resist, oxide, nitride)
- low substrate temperature during implantation
- little lateral variation/straggling
- dopant concentrations above solubility possible
- good wafer homogeneity (WIWNU< 2 %)
- activation of dopants and healing of radiation damage is necessary
- possibility of shallow doping
- complex equipment

WIWNU – within wafer nonuniformity

3.5.2 Applications of Ion Implantation in Microelectronics

Application	Dose (ions / cm^2)
Unipolar Technologies (MOS):	
Source/Drain formation	10^{15} ... $5 \cdot 10^{15}$
Low doped drain (LDD)	10^{13} ... 10^{14}
Channel formation (p, n)	10^{11} ... 10^{12}
Well formation (CMOS, n, p)	10^{13} ... 10^{14}
Channel stopper	10^{13} ... 10^{14}
Salicide (self aligned silicide formation)	ca. $5 \cdot 10^{15}$
Hillock suppression for interconnects (Ar^+ in Al)	ca. 10^{16}
Doping of poly Si	10^{15} ... 10^{16}
Bipolar Technologies:	
Base formation	$5 \cdot 10^{13}$ ... $5 \cdot 10^{14}$
Emitter formation	10^{15} ... 10^{16}

Applications of Ion Implantation in CMOS IC Fabrication

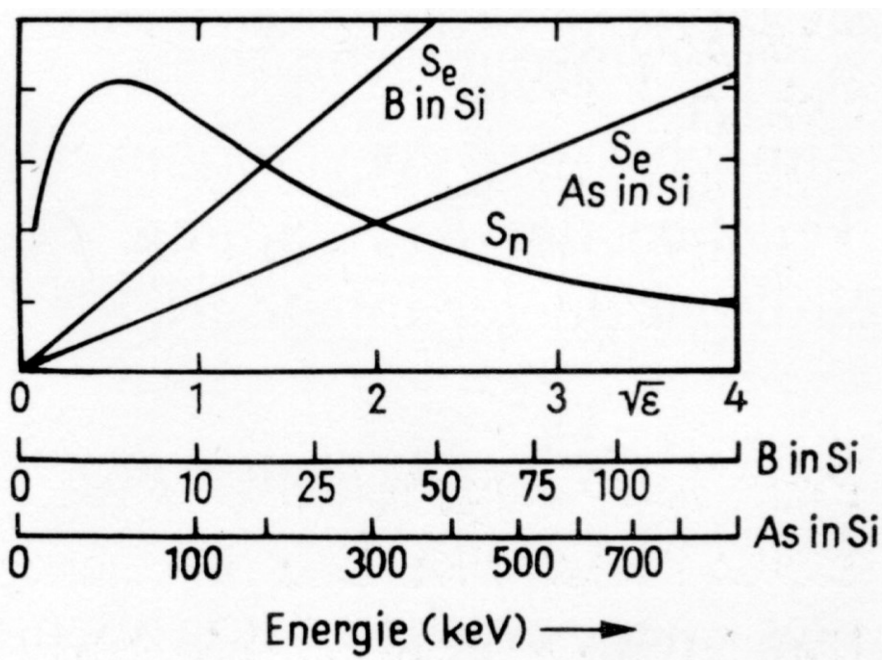


3.5.3 Ion-Solid Interaction

Ions lose energy within the solid mainly by
- (elastic) nuclear collisions
- inelastic interactions with electrons of the target

$$\text{Energy loss :} \qquad -\frac{dE}{dx} = N\left(s_n(E) + s_e(E)\right)$$

E - ion energy
N - atomic density of the target
s_n - nuclear stopping power
s_e - electronic stopping power



Electronic stopping is dominating at high energy.

Nuclear stopping is more effective at lower energy.

Calculation of dopant distribution for amorphous targets:

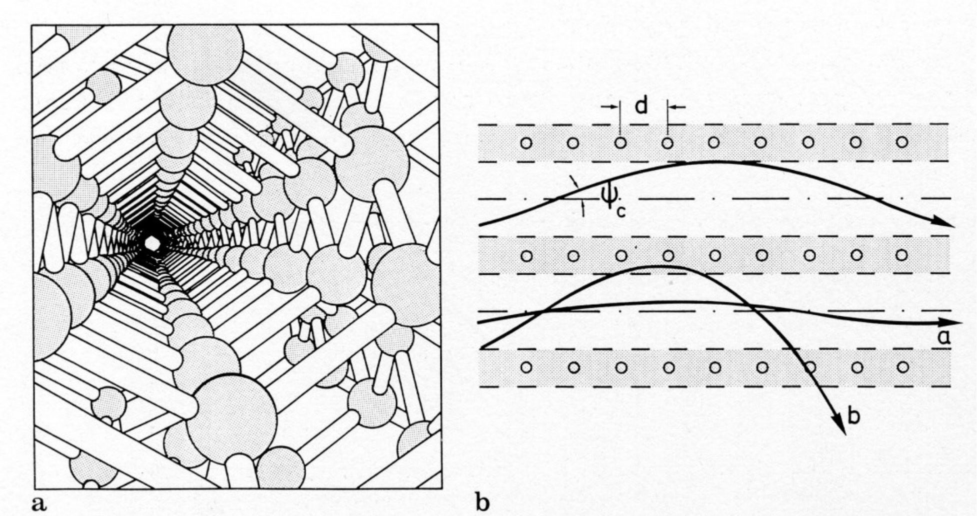
LSS Theory

(Lindhardt, Scharff und Schiott)

Channeling

Ions lose considerably less energy if they travel trough the crystal along low-index directions (i.e. if the angle between trajectory of the ion and a low-index direction is less than a characteristic critical angle Ψ_c)

Prevention:
- Inclination of the ion beam against the surface normal of the wafer (minimum channeling at 7° ...10°)
- Amorphous cover layers (scattering oxide)
- Pre-amorphization (e.g. Si^+ in Si)



View along Si<110> Various ion trajectories

Ion	Energy (keV)	Critical angle ⟨100⟩	⟨110⟩	⟨111⟩
Bor	10	4,76	6,97	5,30
	100	2,67	3,47	2,98
	300	2,03	2,98	2,26
Phosphor	10	5,79	7,51	6,45
	100	3,26	4,22	3,63
	300	2,47	3,21	2,76
Antimon	10	6,95	9,01	7,74
	100	3,91	5,07	4,35
	300	2,97	3,84	3,31

Critical angle for dopants in Si

3.5.4 Modeling of Dopant Distributions

Model

Gaussian distribution

$$N(x) = C \frac{Q}{\Delta R_P \cdot \sqrt{2\pi}} \cdot \exp\left(- \frac{(x - R_P)^2}{2 \cdot \Delta R_P{}^2} \right)$$

R_p - mean projected range [µm]
DR_p - mean projected range straggle [µm]
x - depth [µm]
N(x) - dopant distribution [cm^{-3}]
Q - dose [cm^{-2}]

$$C = \frac{2}{1 + \mathrm{erf}\left(\frac{R_p}{\sqrt{2}\Delta R_p} \right)}$$

- normalization factor,

ensures that $Q = \int_0^{+\infty} N(x)\,dx$

$C \sim 1$ for $R_p/\Delta R_p > 2$

Pearson IV distribution

four moments: R_p
DR_p
skewness
kurtosis

Comments on validity

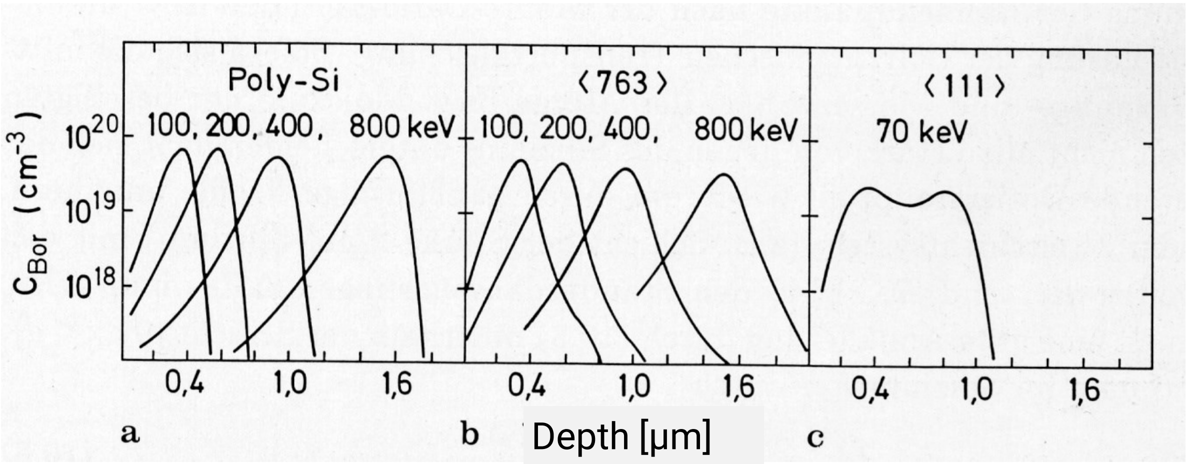
Gaussian distribution:

- *LSS theory yields Gaussian profile with the two moments R_P and ΔR_P.*
- *good agreement with experimental data for amorphous targets*
- *no channeling*
- *problems with cover layers*

Pearson IV distribution:

- *better agreement with experimental data for all amorphous materials*
- *no channeling*
- *problems with cover layers*

Model	***Comments on validity***
Pearson IV distribution with exponential tail	– *good agreement also for crystalline materials, can account for channeling* – *problems with cover layers*
Boltzmann Transport Equation (BTE)	– *BTE predicts profile in amorphous silicon also if cover layers are present.* – *no channeling*
Monte Carlo Approach (MC)	– *universal approach, predicts dopant profiles in both amorphous and crystalline materials even when surface layers are present*



Distribution of B after implantation

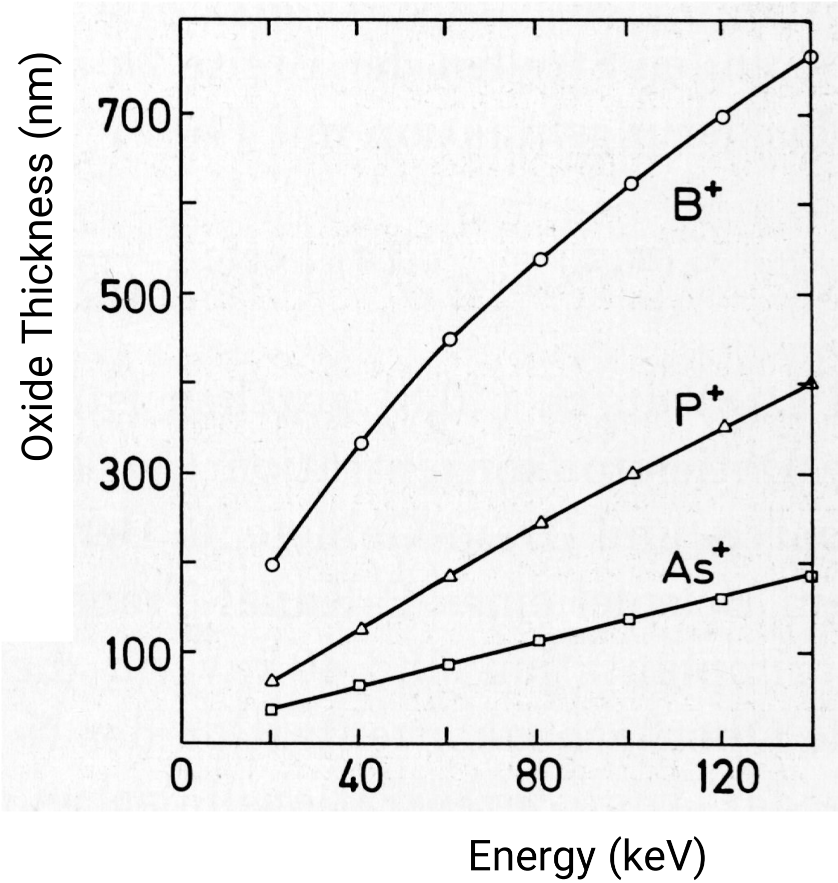
a) in poly crystalline Si

b) in single crystal Si along the <763 > direction

c) in single crystal Si along the <111 > direction

/Schumicki/

Minimum Thickness of Mask Oxide



3.5.5 Healing Up of Radiation Defects and Dopant Activation

Objectives of annealing:

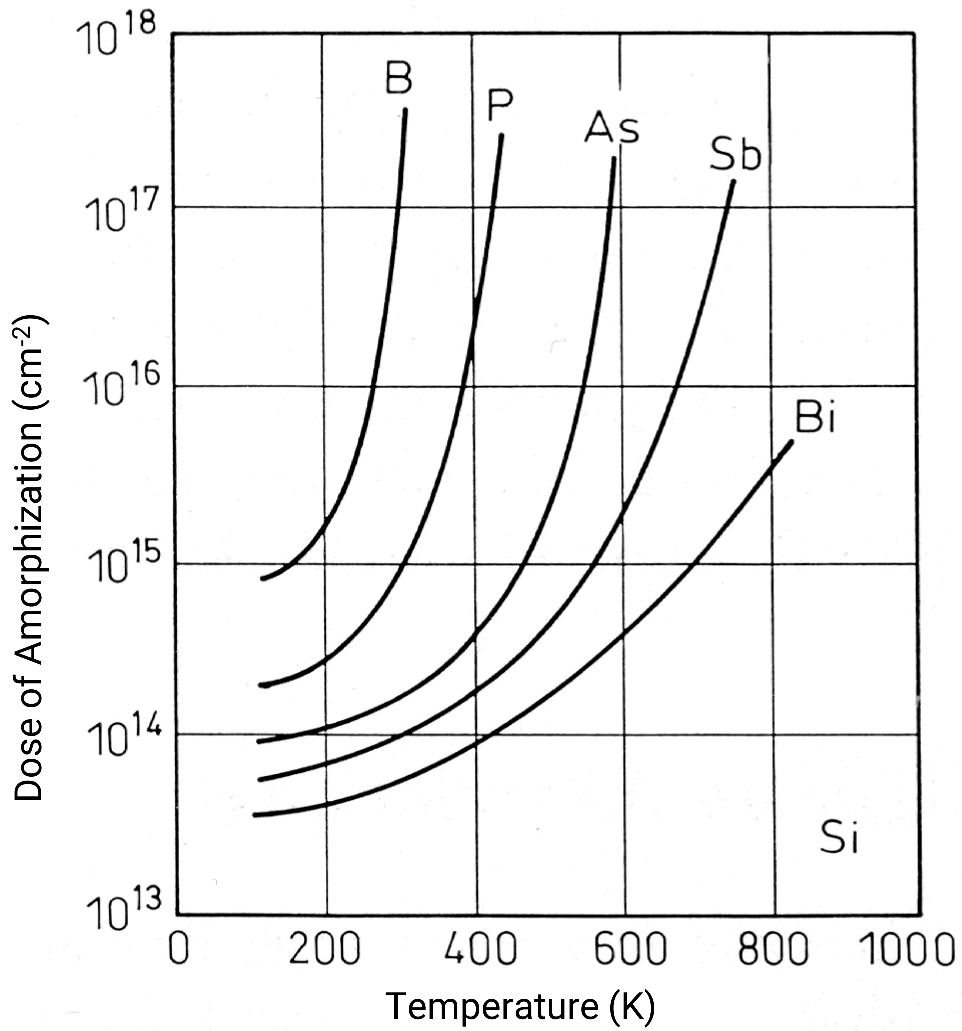
- High degree of **dopant activation**
  (depends on temperature, about 900 °C are necessary for Si)
- Achievement of superior **crystal properties** (mobility μ, Minority life time τ)

Effects of annealing for Si:

T [°C]	Characteristics
450	partial activation, ca. 20 ... 50 % of bulk values
550	50 % activation for boron, less for other dopants
660	recrystallization of amorphous silicon (a-Si) 50 % activation after high-dose implantation
800	20 % activation after high-dose implantation of boron, 50 % for other dopants
900	achievement of bulk mobility, 90 ... 100 % activation

NOTE: Diffusion is taking place simultaneously

Dependence of the dose of amorphization of silicon on temperature for several ions

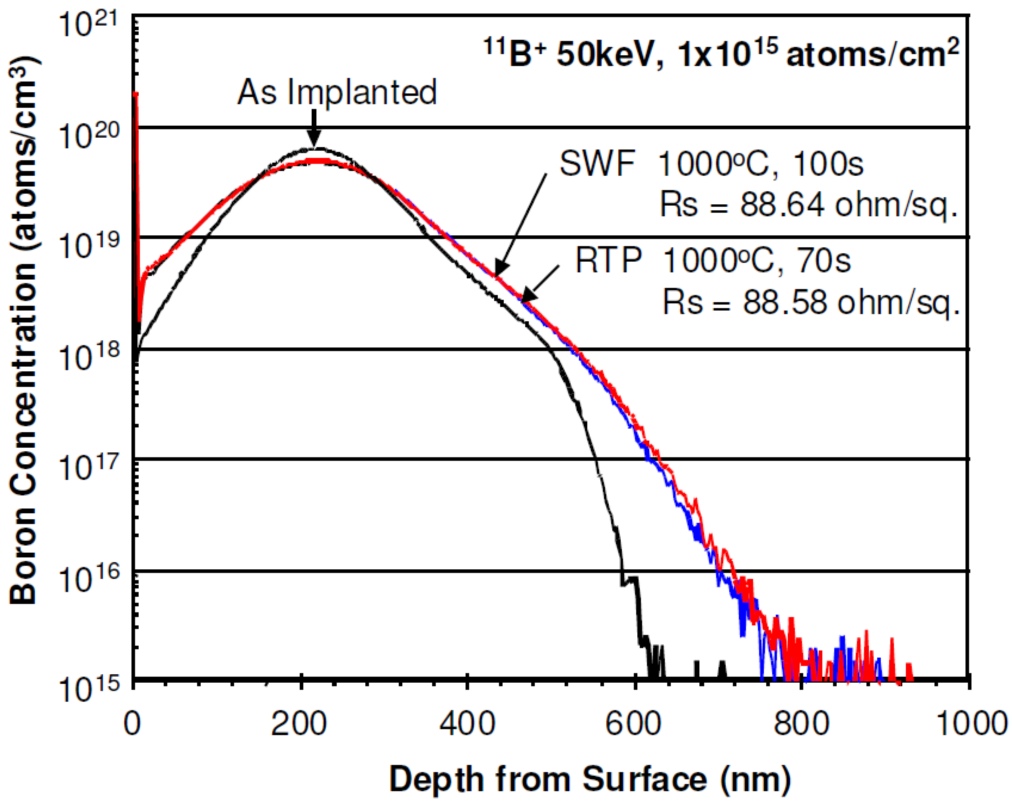


Methods of Annealing

Annealing method	Process temperatures in °C	Process time	Broadening of profiles during process time at T = 1100 °C
– Furnace (e.g. in N_2, H_2)	900 - 1100	min, h	1 µm (1000 s)
– Rapid thermal processing (RTP)	1000 - 1250	s	0.1 µm (10 s)
– Flash lamp	1000 - 1300	ms	0.01 µm (0.01 s)
– Laser	1100 - 1400	µs	< 0.01 µm (0.01 s)

Doping profiles after implant and after annealing

SIMS depth profiles of as implanted wafer and wafers after annealing in SWF and lampbased RTP systems.



Comparison: single wafer furnace (SWF) system and a lamp-based RTP system under 1 atm N2 atmosphere

Woo Sik Yoo et al., Comparative Study on Implant Anneal using Single Wafer Furnace and Lamp-based Rapid Thermal Processor

3.5.6 Equipment

Ion Implanter Types

- Low-energy implanters	0.2 ... 80 keV	
- Medium-energy implanters	20 ... 200 keV	
- High-energy implanters	0.5 ... 3 MeV	
- Medium current implanter (MCI)	0.1 ... 3 mA	up to 1E15 ions/cm^2
- High current implanter (HCI)	3 ... 100 mA	up to 1E16 ions/cm^2

Implanted Dose:

$$Q = I \cdot t / (A \cdot n \cdot q_0)$$

n - charge state (onefold, twofold charged ions)
q_0 - elementary charge
I - beam current
t - implantation time
A - scanned area

Throughput per h:

$$TP = \frac{3600s \cdot Z \cdot K}{t_P + t_H}$$

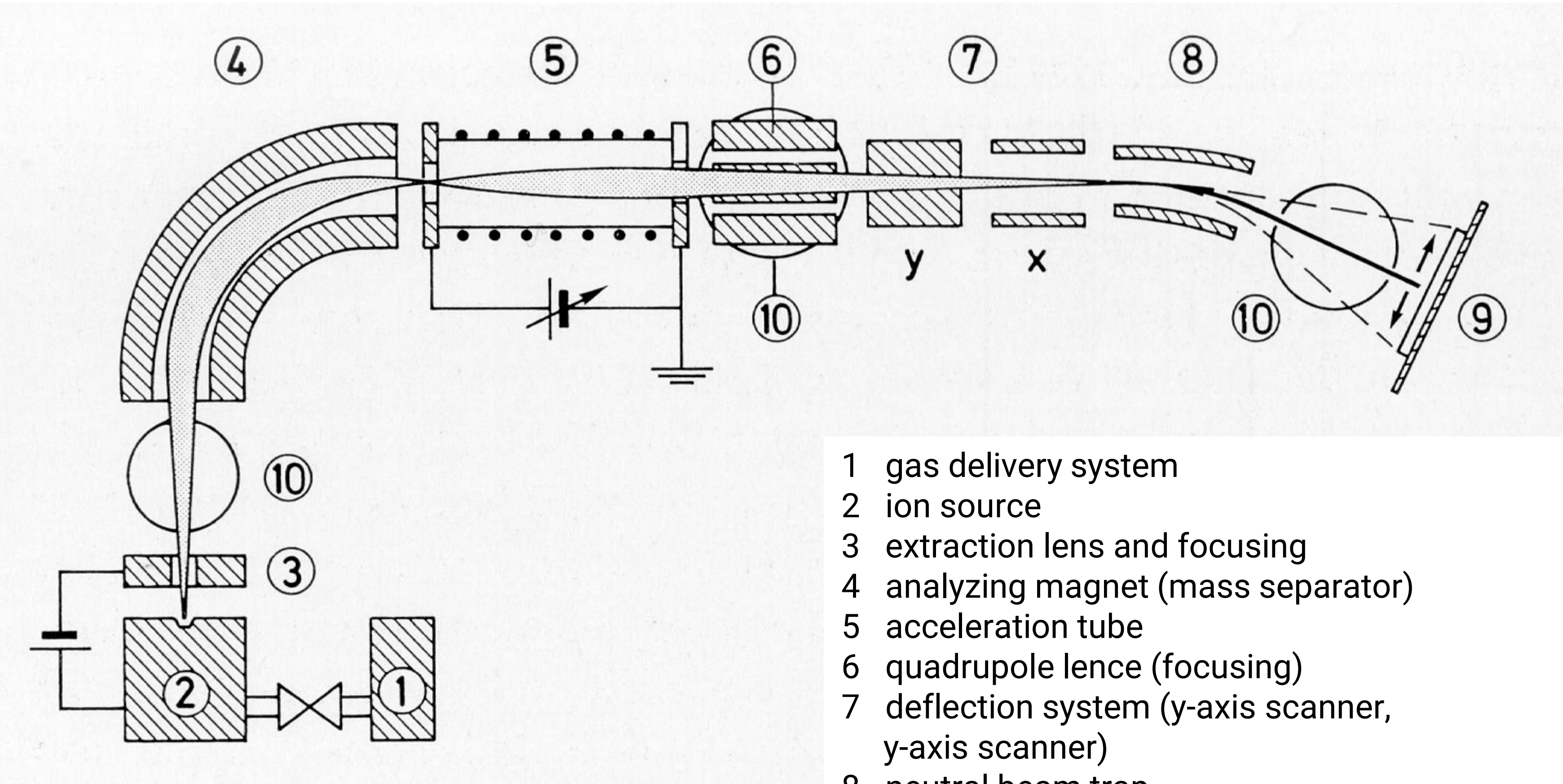
Z - number of wafers per load station
K - number of load stations

batch implant time [s]

handling time between implants [s]

Typical values: **MCI**: 100 ... 200 wafers/h, **HCI**: 300 ... 400 wafers/h

Schematic set-up of an implantation tool



1 gas delivery system
2 ion source
3 extraction lens and focusing
4 analyzing magnet (mass separator)
5 acceleration tube
6 quadrupole lence (focusing)
7 deflection system (y-axis scanner, y-axis scanner)
8 neutral beam trap
9 wafer in process chamber
10 vacuum system

Ions before and after mass separation

Source material	Ions before mass separation	Ions after mass separation
BF_3 (gas)	B^+, BF^+, BF_2^+, F^+, F_2^+	B^+ or BF_2^+
PF_5 (gas)	P^+, PF^+ ... F_2^+, P_2^+	P^+
AsF_3 (liquid)	As^+, AsF^+ ... F_2^+	As^+

Uniformity of implanted dose:

Within-Wafer-Nonuniformity (WIWNU):	1 ... 2 %
Wafer-to-Wafer-Nonuniformity (WTWNU):	< 5 %

Schematic set-up of an implantation tool