Applications of Ion Implanters

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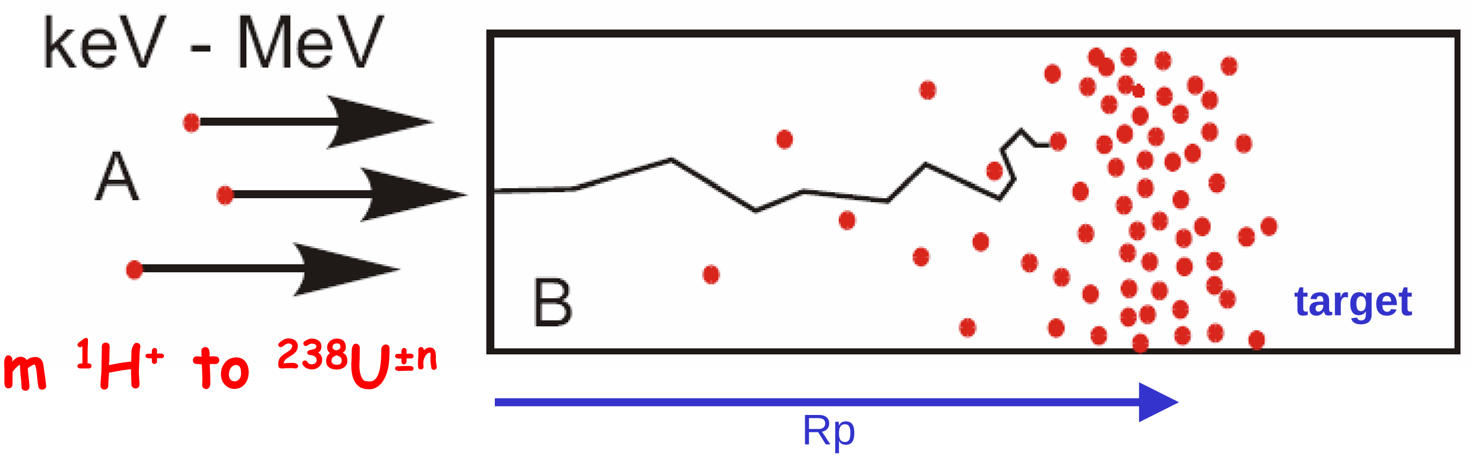
ION IMPLANTATION

More than a standard technique for the doping of semiconductor devices



... from $^{1}H^{+}$ to $^{238}U^{\pm n}$

The technique for the

- controlled insertion of atoms into a near surface layer

- nanoscale modification of structural properties

Fundamental terms

dose (fluence) = number of ions per area [cm^{-2}]

dose rate (flux) = dose per time [$cm^{-2}s^{-1}$]

projected range R_p = mean penetration depth beneath surface

What is an Ion Implanter ?

.... any machine implanting ions into solids* at energies of

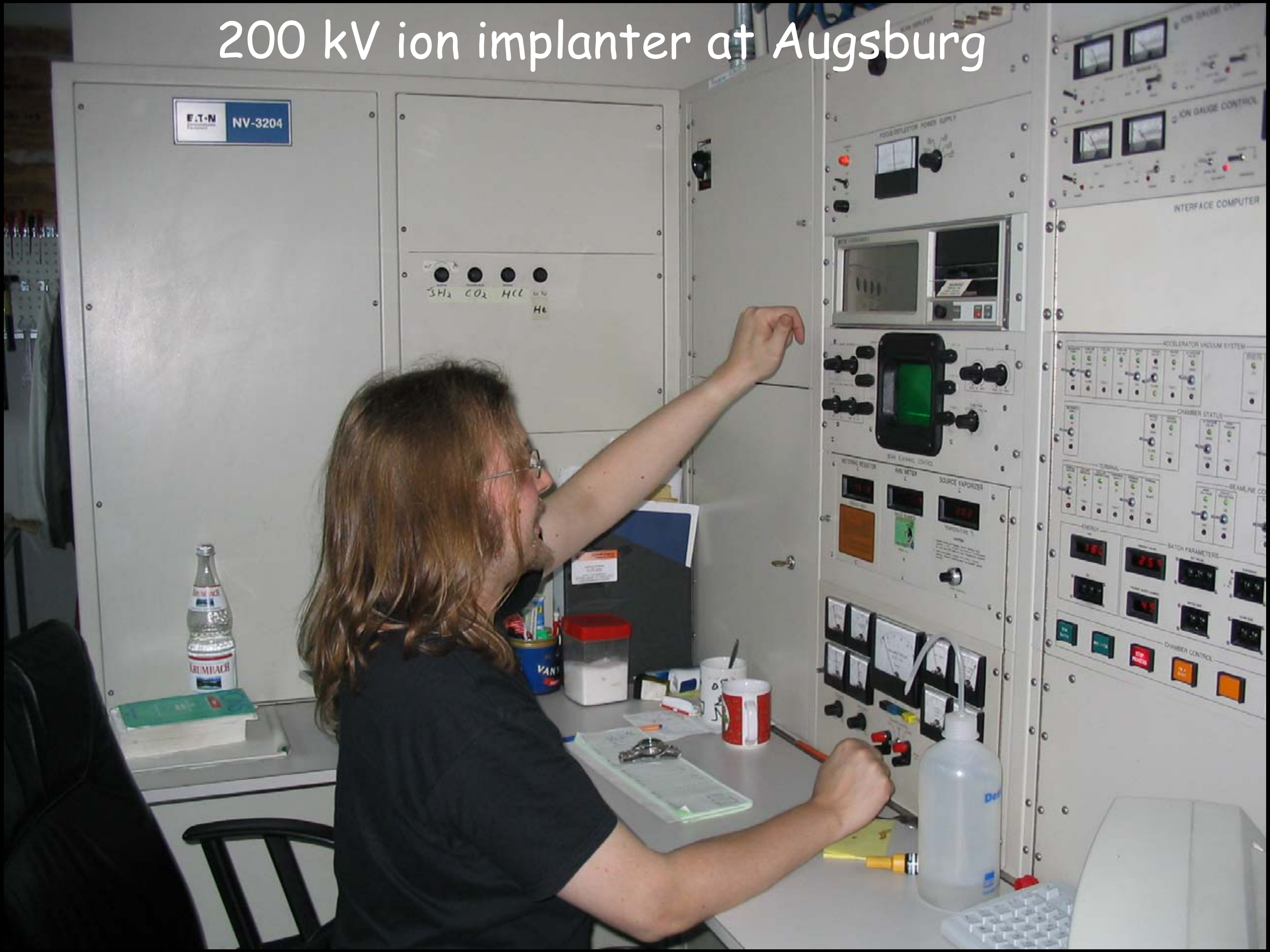
~ 500 eV - 500 MeV

not included in this talk:

- ion sources (for sputtering, surface smoothing ...)
- ion beam assisted deposition apparatusses
- plasma immersion ion implantation
- cluster ion set-ups
- focused ion beams

* and maybe organics

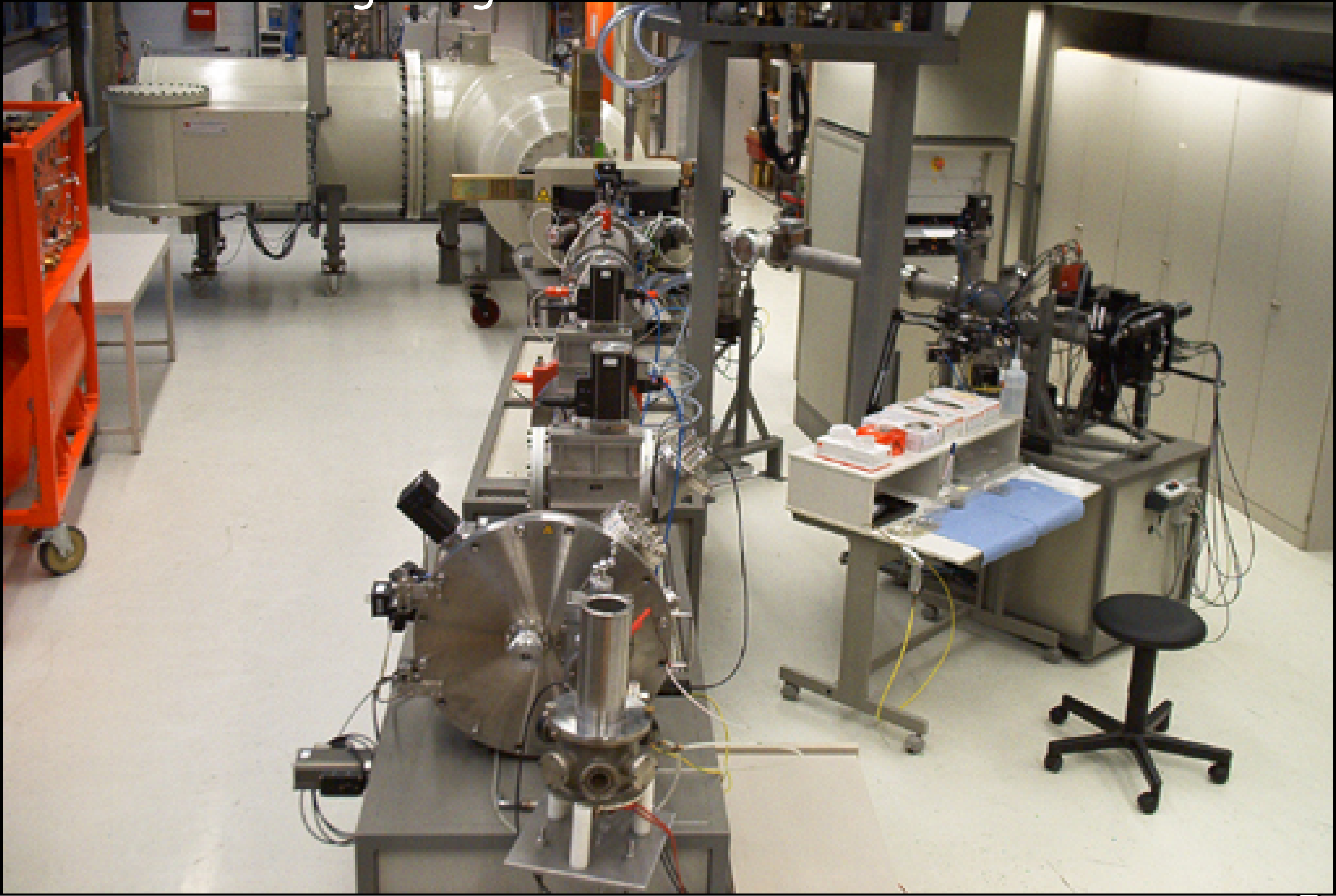
200 kV ion implanter at Augsburg



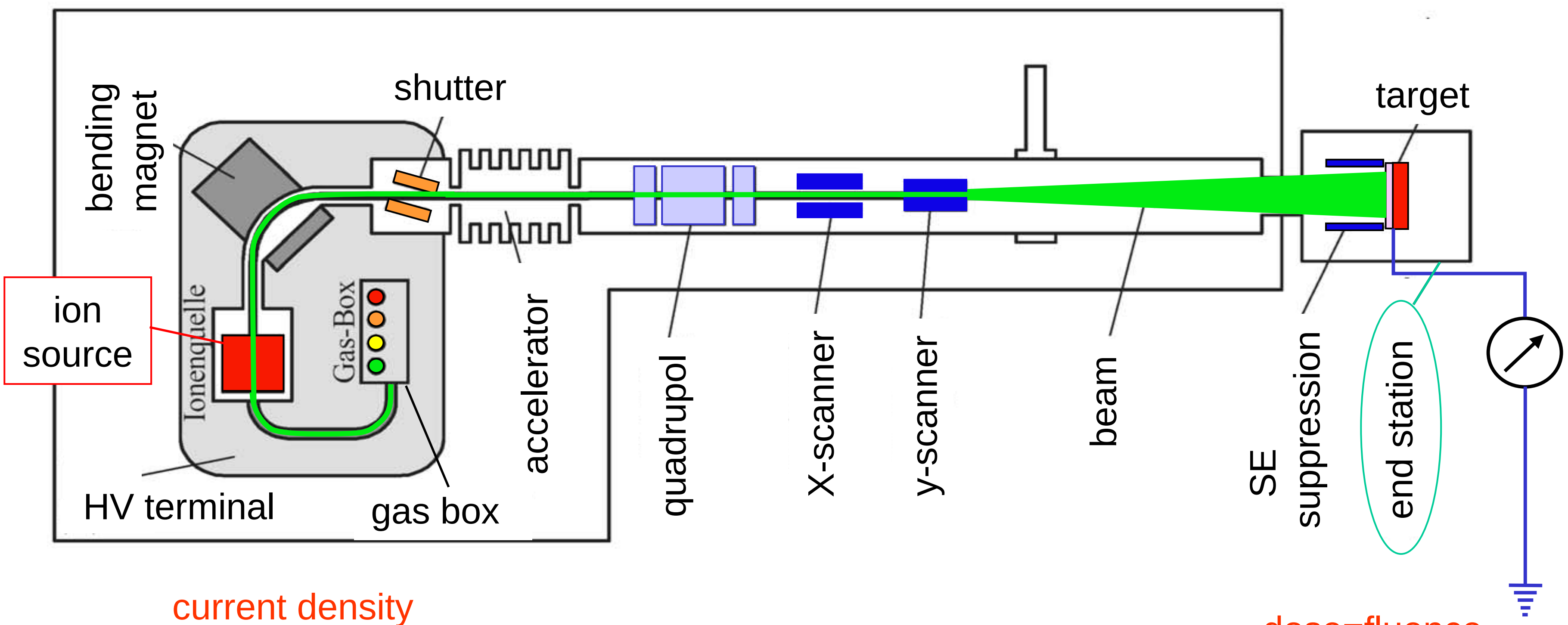
200 kV ion implanter at Louvain

http://www.dice.ucl.ac.be/

Augsburg 2 MV Tandem Accelerator



Ion Implanter – Beam Line



isotope/charge state

energy

irradiated area / homogenity

angle of incidence

temperature

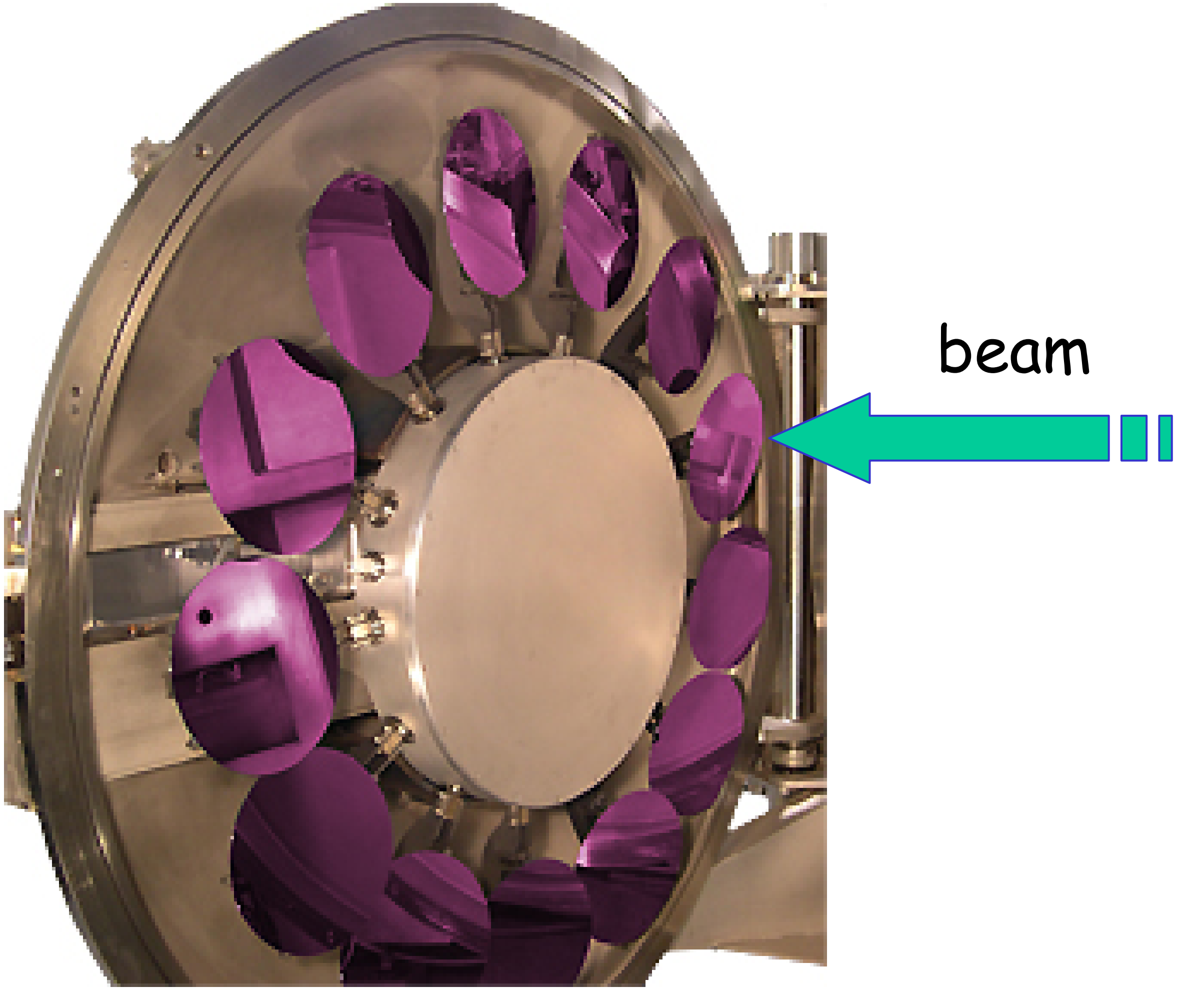
current density

dose=fluence

Wafer Handling System of an Implanter Endstation

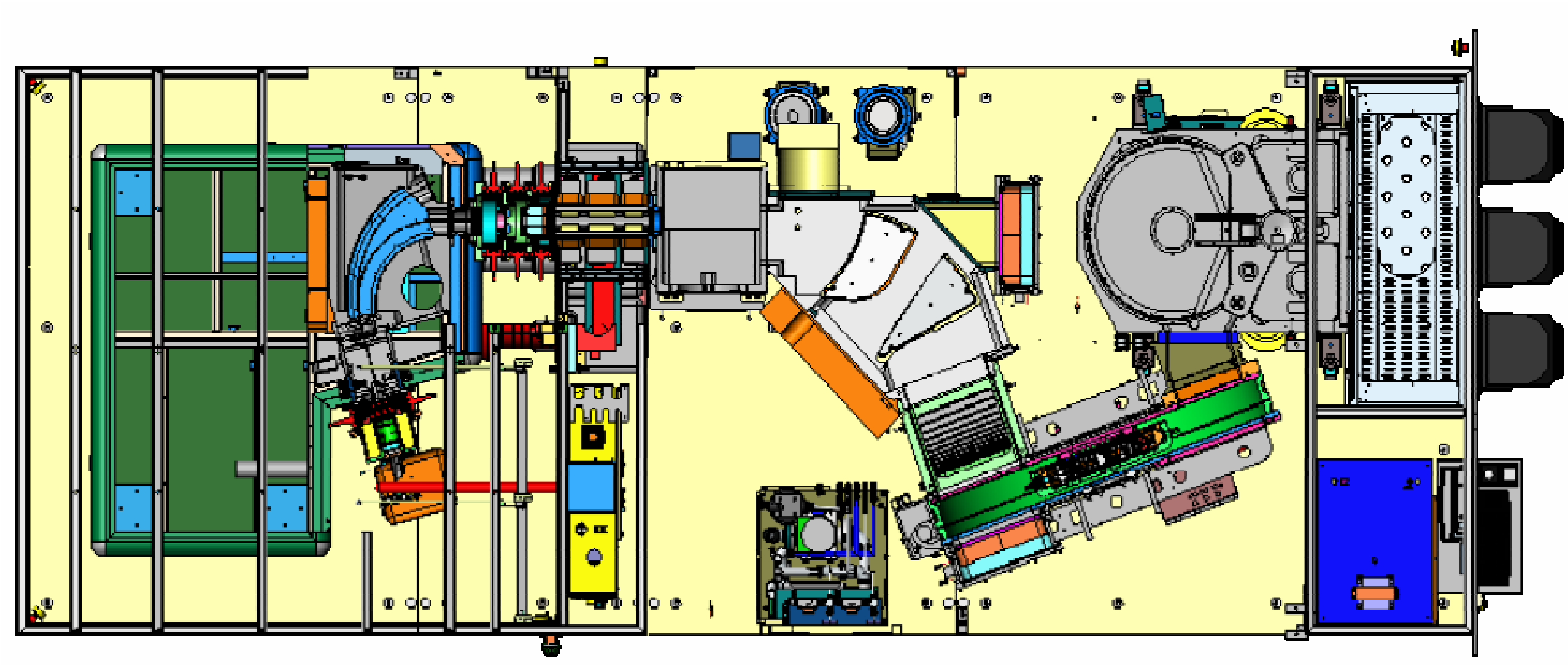
http://www.axcelis.com/......Paradigm.jpg

Rotating Wafer Hub



http://www.ibis.com/2000.htm

Plan view of a dedicated high-dose oxygen implanter



J. Blake et al., IIT2002 conf.

65 - 230 keV
≤ 100 mA O^+ → ~20 kW beam

72 kW lamp heater,
T_i= 300 - 570°C,
$t_{heat-up}$ = 5 min.
13/20 wafers, Ø=300/200 mm

Requirements for semiconductor doping

Today:

95 % of all doping steps done by implantation

CMOS-IC with memory:

up to 35 implantation steps

Price per transistor:

< 20 nano-US$

Throughput: ~ 250 wafers/h, 150, 200, 300 mm Ø, incl. wafer handling

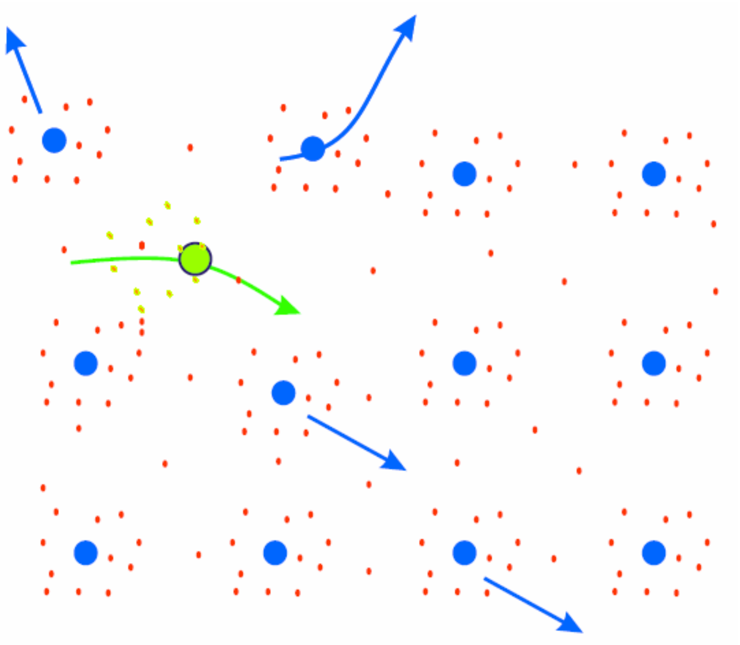
Dose uniformity: 3σ = 1.5 % on 300 mm Ø target
Wafer-to-wafer repeatability, batch-to-batch
Energy variation: 3σ = 3 %
Implant angles: ≤60°, 3σ = 1°
Metal contamination (Fe, Ni, Cu, Cr, Zn): < 5 x 10^{10} cm^{-2}

- 1980-2005: 6000 implanters
- Capacity up to 270 wafers/h
- Assuming 4000 in operation: mass transfer of **18 g/h**

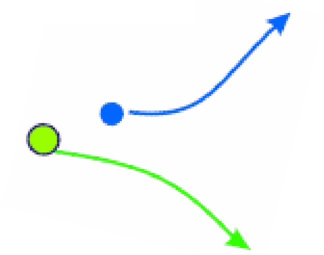
What happens when an ion hits a target ?

Ion-Implantation: Stopping Mechanisms

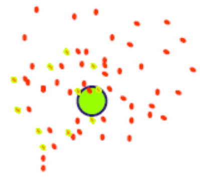
For ions in the eV to 10^2 MeV region, only two stopping mechanisms are important:



1) Elastic collisions of ions and nuclei,
nuclear stopping power



2) Inelastic collisions of ions and electrons,
electronic stopping power



The two contributions are treated independently, nuclear stopping approximated as a sequence of binary collisions:

Stopping cross section S:

$$S = -\frac{1}{N}\left(\frac{dE}{dx}\right) = S_n + S_e = -\frac{1}{N}\underbrace{\boxed{\left(\frac{dE}{dx}\right)_n}}_{\text{nuclear}} + -\frac{1}{N}\underbrace{\boxed{\left(\frac{dE}{dx}\right)_e}}_{\text{electronic}}$$

Stopping power [eV/A]

Stopping of Ions in Matter: Energy Dependence

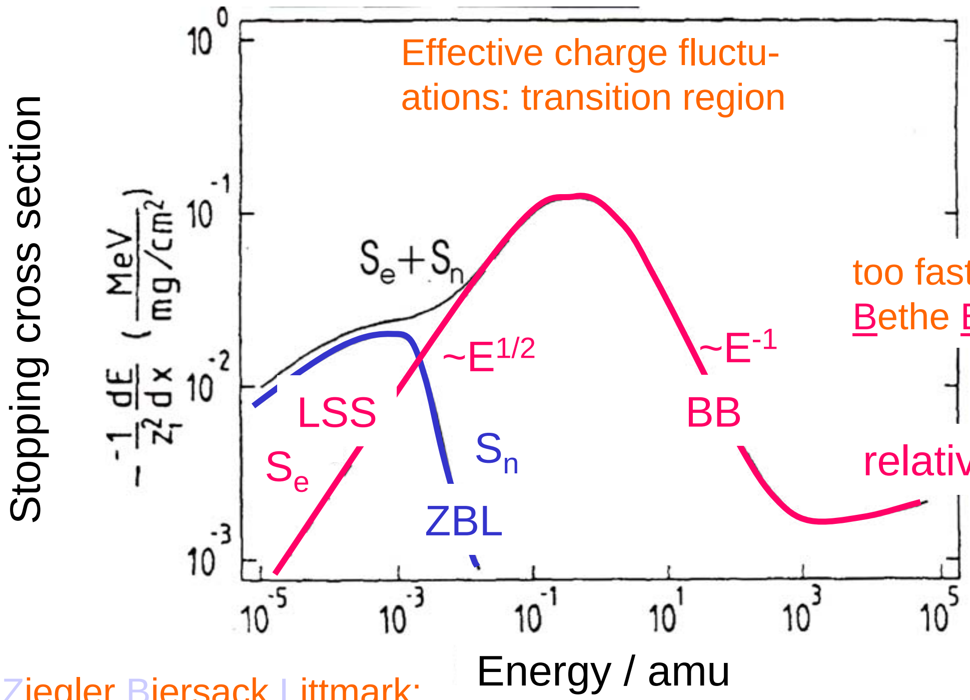
Stopping cross section S:

stopping power ~ velocity: LSS region

$$S = -\frac{1}{N}\left(\frac{dE}{dx}\right) = S_n + S_e = -\frac{1}{N}\left(\frac{dE}{dx}\right)_n - \frac{1}{N}\left(\frac{dE}{dx}\right)_e$$

Stopping power nuclear electronic

N: target density



Effective charge fluctuations: transition region

too fast to ionize: Bethe Bloch region

relativistic region

Ziegler Biersack Littmark: universal potential

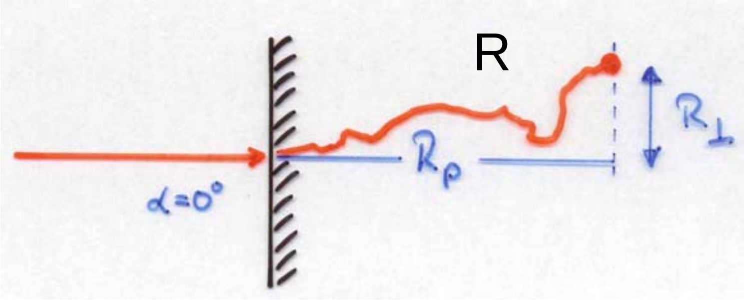
nuclear stopping dominates at low energies

electronic stopping dominates at high energies

Ion Profiles

Ion ranges calculated from stopping cross sections:

$$R = \frac{1}{N}\int_0^E \frac{dE}{S_e(E) + S_n(E)}$$



With atomic target density N.

Statistics of collisions: → range distributions. One measures mean projected range R_p and standard deviation ΔR_p. Best description as Pearson IV distribution, but often Gauss approx:

$$C(x) = \frac{D}{\sqrt{2\pi}\,\Delta R_p}\exp\left(-\frac{(x-R_p)^2}{2\Delta R_p^2}\right)$$

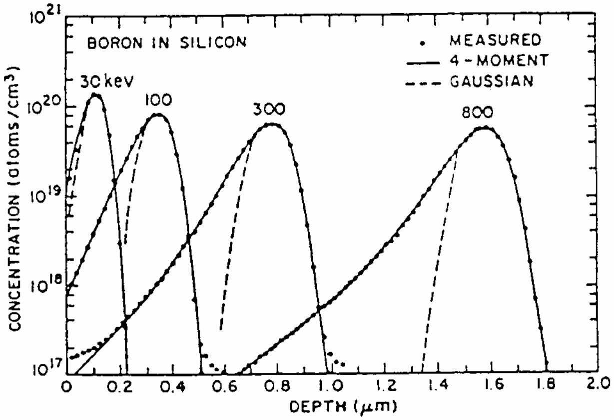


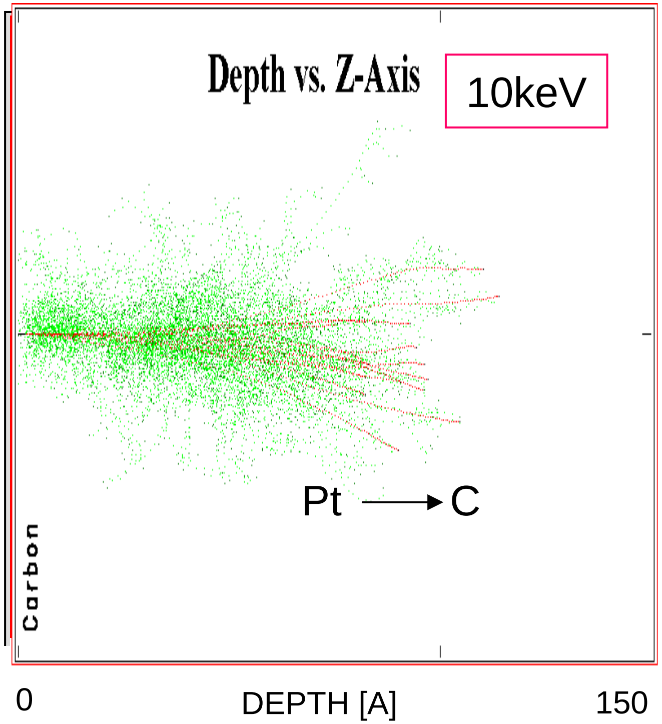
Figure 3.8 *Experimental B profiles into polycrystalline silicon (from ref. 3.16). The four moment distributions are calculated with the following β values (800 keV - 60; 300 keV - 19; 100 keV - 7; 30 keV - 3.6).*

Monte-Carlo-Simulation of Ion Profiles

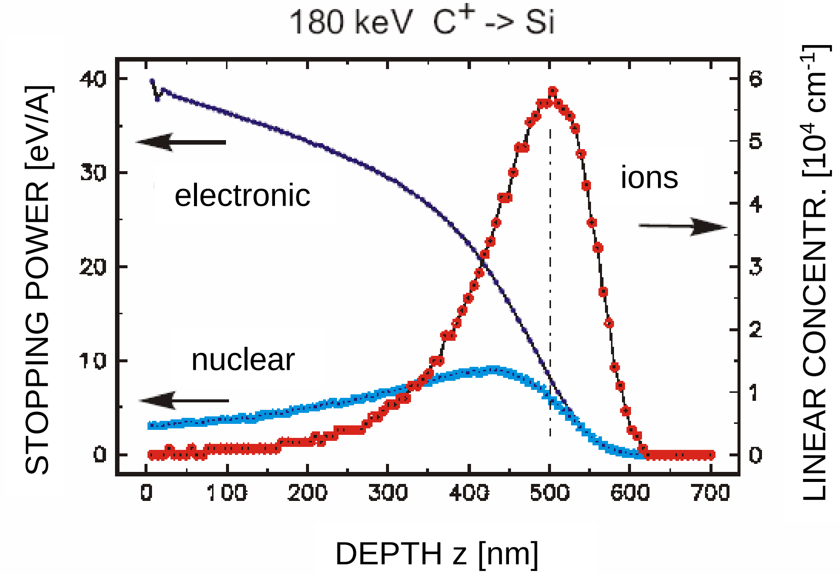
Profile calculation of many (~10^5) ion trajectories via Monte-Carlo simulation of collision statistics.

Popular code: SRIM or TRIM (Stopping and Range of Ions in Matter).

Public domain program @ http://www.srim.org/



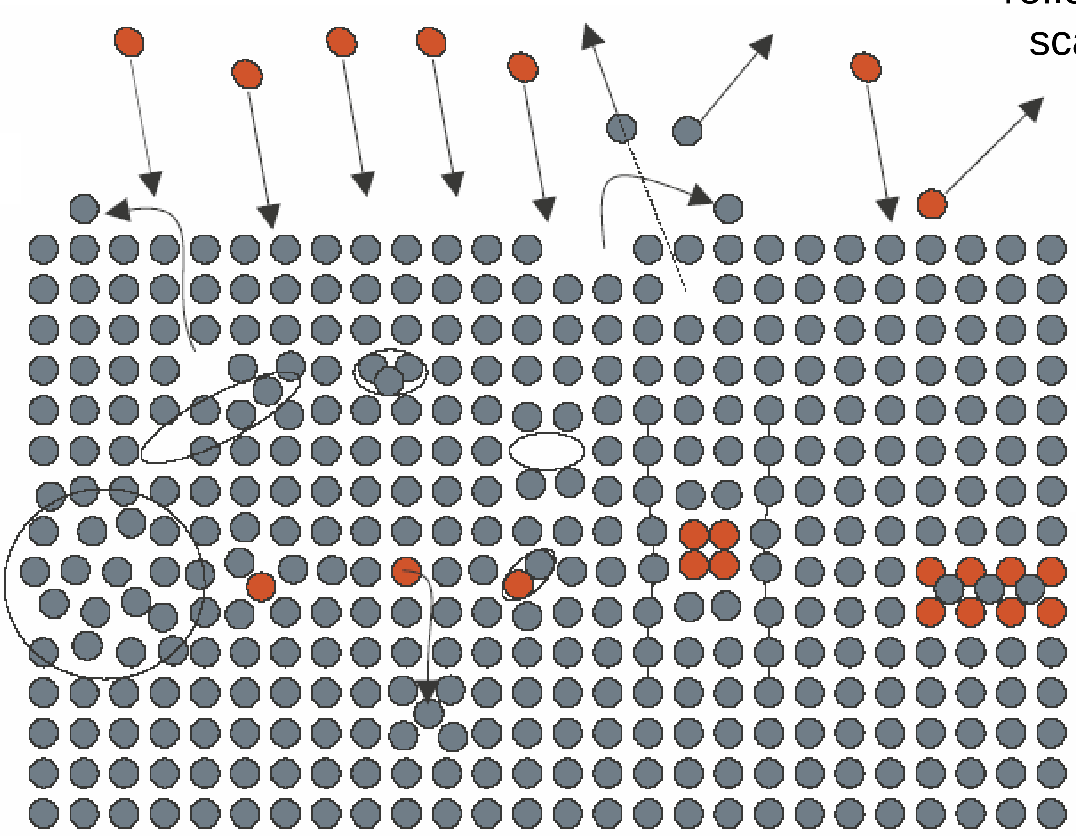
Example



Some warnings:

- Accuracy of R_{max} 5% for keV, 10% for MeV ions
- SRIM/TRIM does NOT calculate the damage !
- High dose effects (sputtering, density changes, stopping power changes) not taken into account

Ion-Solid-Interactions: Structural Changes



impinging ions

sputtered atoms

reflected + back-scattered ions

adatoms

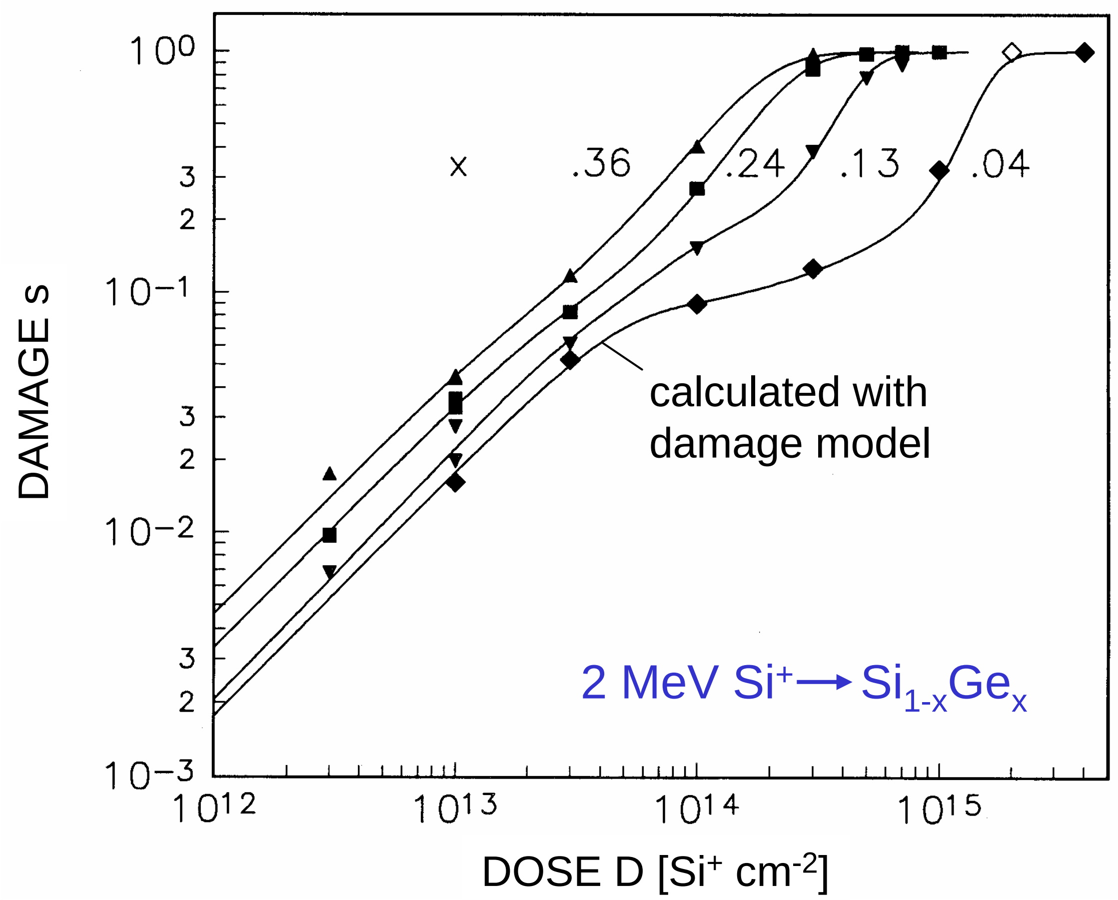
point defects / clusters

coherent / incoherent precipitates

amorphous volumes

interstitial/substitutional impurities

Radiation damage and amorphization



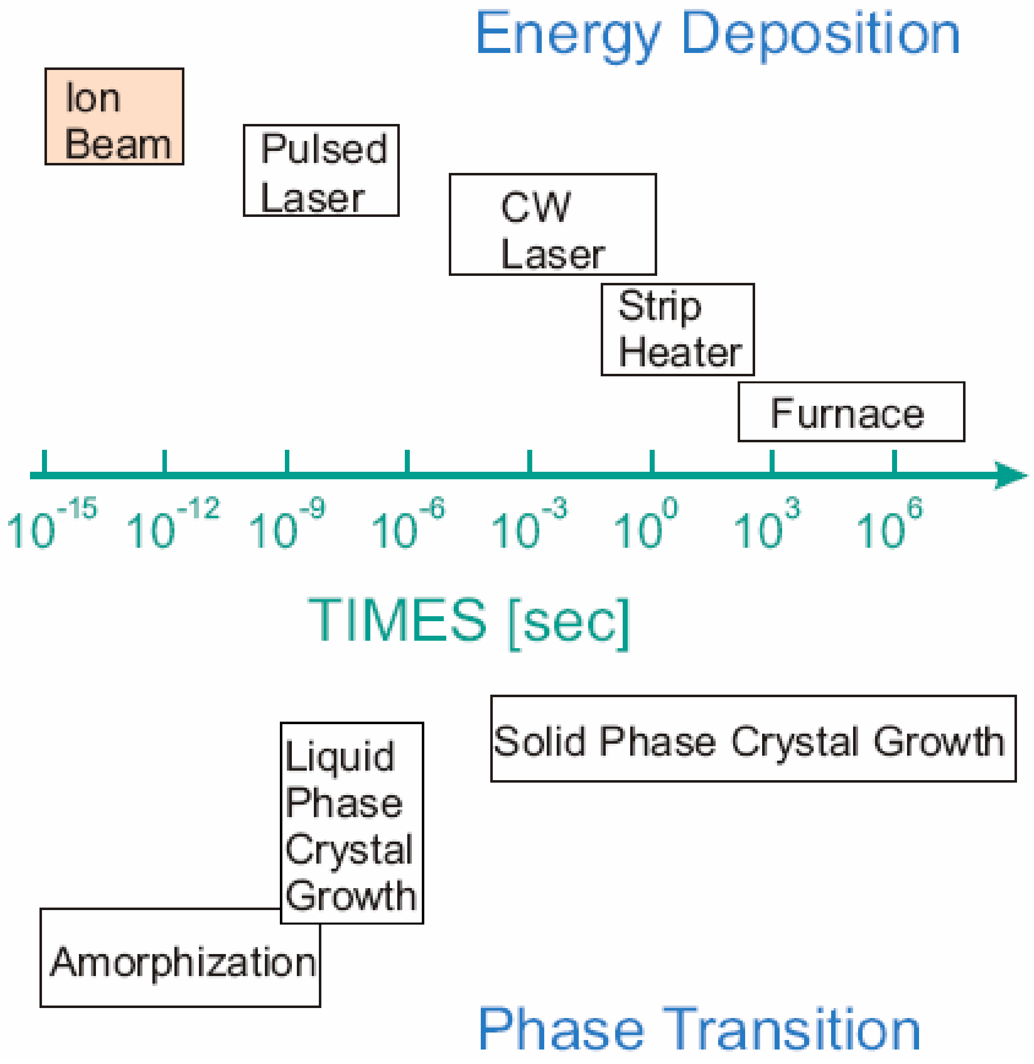
J.K.N.L., NIM B 127 (1997)

damage saturation by amorphization

Damage accumulation is a highly non-linear process!

Data for many ion/target combinations available but no *general* model

Ion-Solid-Interactions: Physics over Orders of Magnitude



Energy Deposition

Ion Beam

Pulsed Laser

CW Laser

Strip Heater

Furnace

10^{-15} 10^{-12} 10^{-9} 10^{-6} 10^{-3} 10^{0} 10^{3} 10^{6}

TIMES [sec]

Liquid Phase Crystal Growth

Solid Phase Crystal Growth

Amorphization

Phase Transition

Orders of Magnitude :

20 in time

13 in energy

10 in dose=concentr.

Ion Profiles: Axial and Planar Channeling

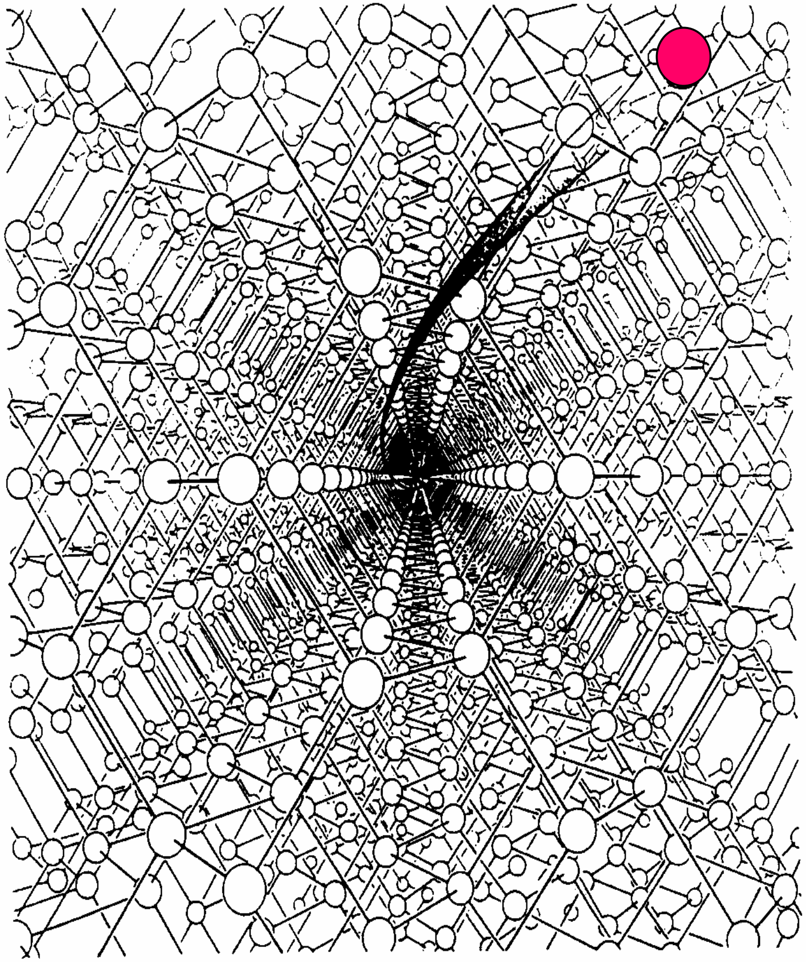
Ions are usually implanted in a “random“ orientation of the target.

If not:

- Ions at low angle of incidence with respect to low index lattice planes or lattice directions see reduced electron and atomic density

Steering along planar or axial channels

Larger ranges
Deformed ion profiles
Reduced lattice damage



Ion Implantation for Semiconductor Devices and Nanostructure Formation

Common Ion Species in Semiconductor Industries

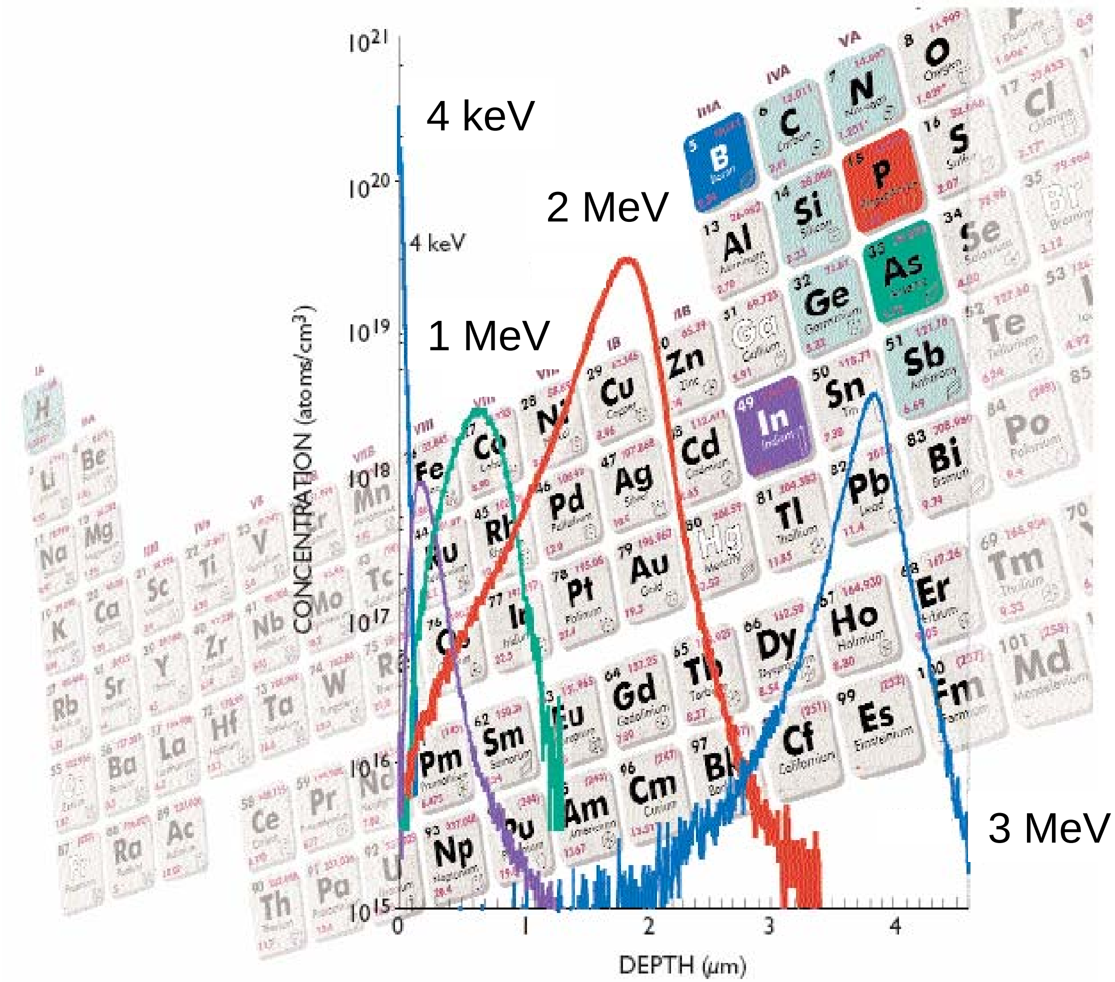
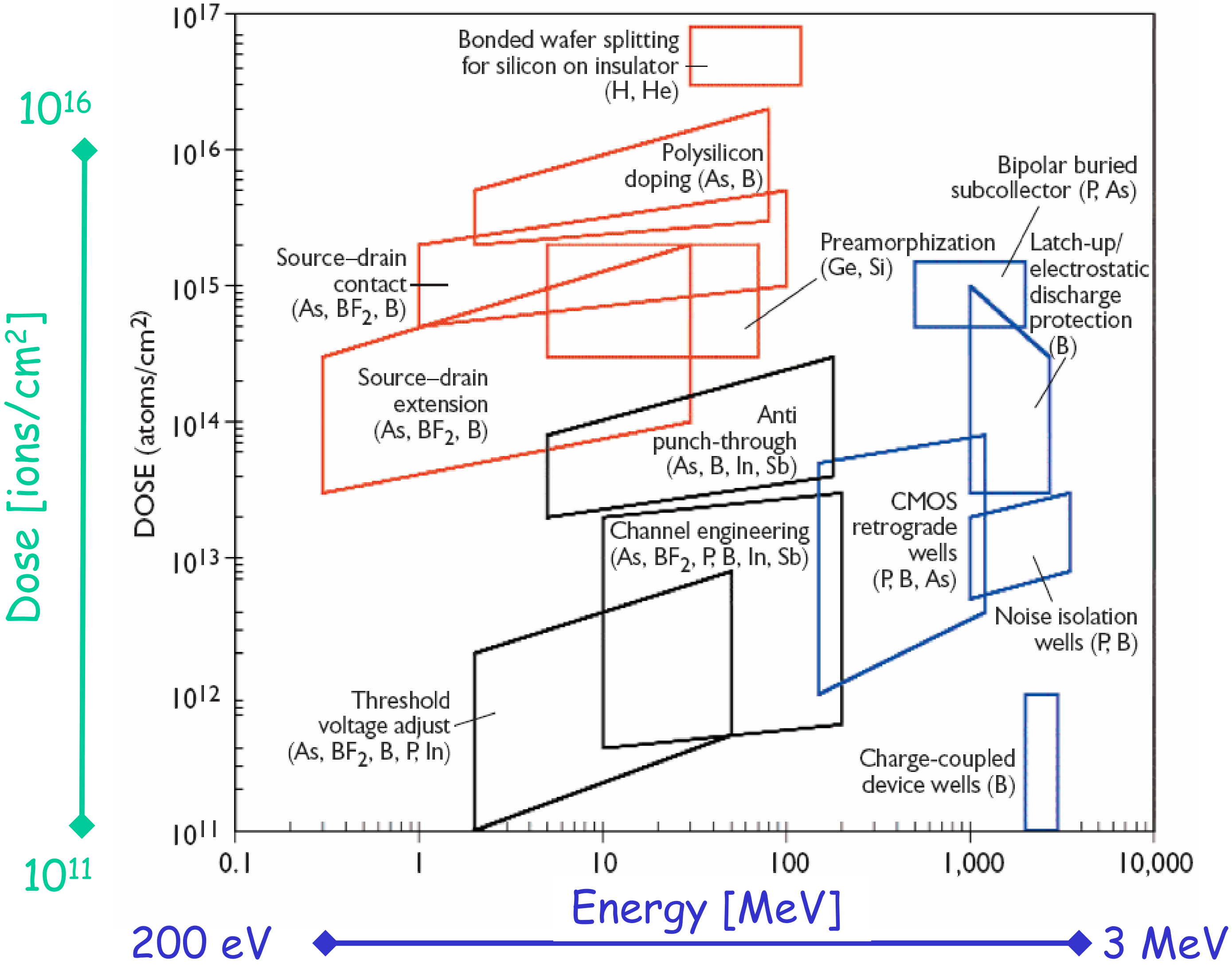


Figure 1. Some of the most commonly implanted species highlighted on the periodic table, along with typical concentration-versus-depth traces for various implant energies.

B BF_2 In	p-type doping
P As Sb	n-type doping
O (N)	buried layers
Si Ge C	preamorphization, strain engineering
H He	wafer splitting

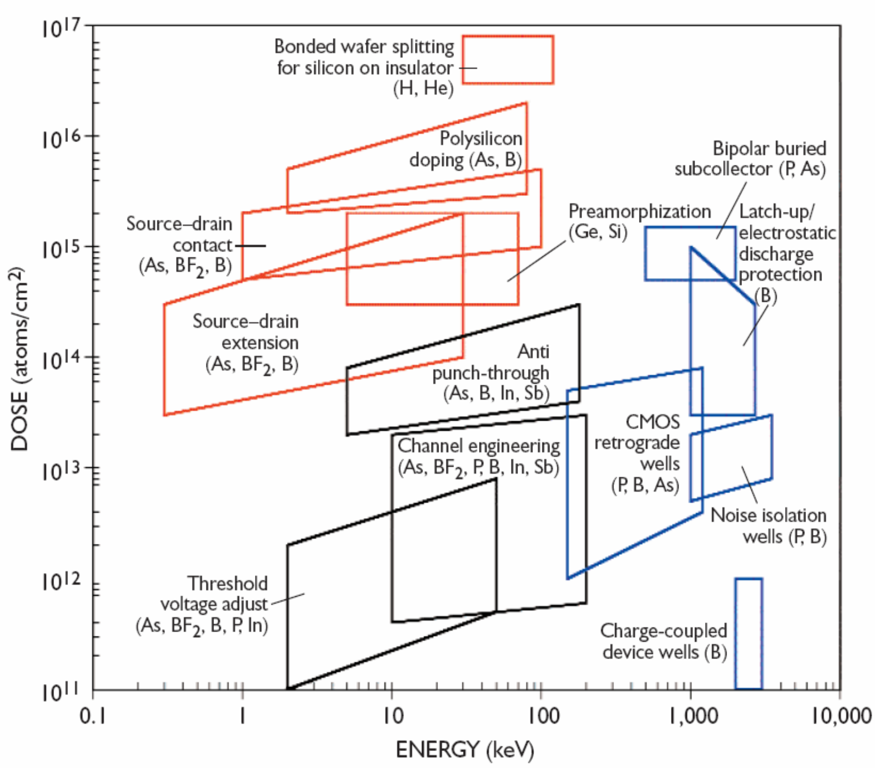
L. Rubin et al., The Ind. Phys. (2003)

Application of Ion Implantation in Semiconductor Industries and Research

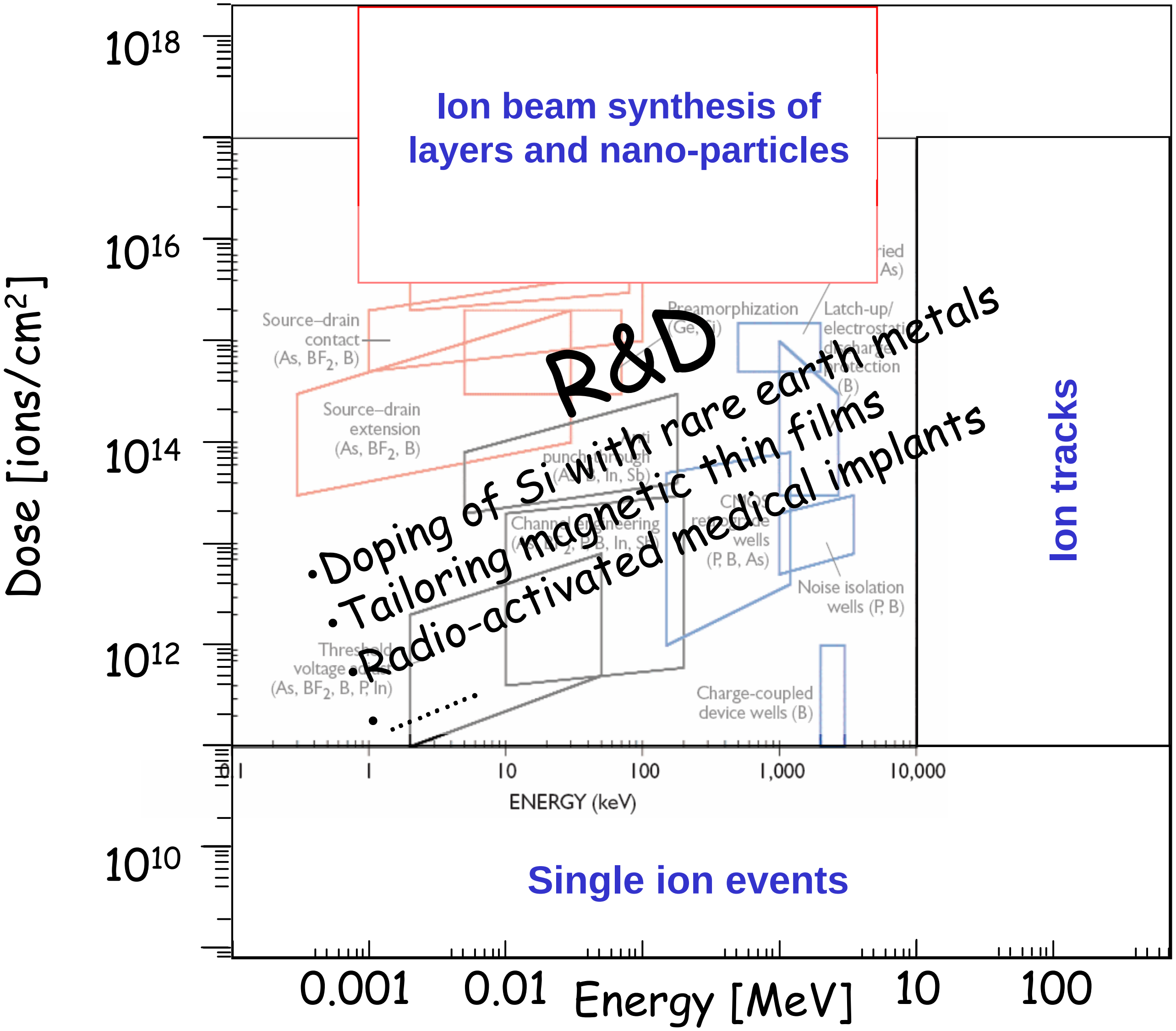


L.Rubin, J.Poate (2003)

Application of Ion Implantation in Semiconductor Industries and Research



Application of Ion Implantation in Semiconductor Industries and Research



Ion beam synthesis of layers and nano-particles

R&D

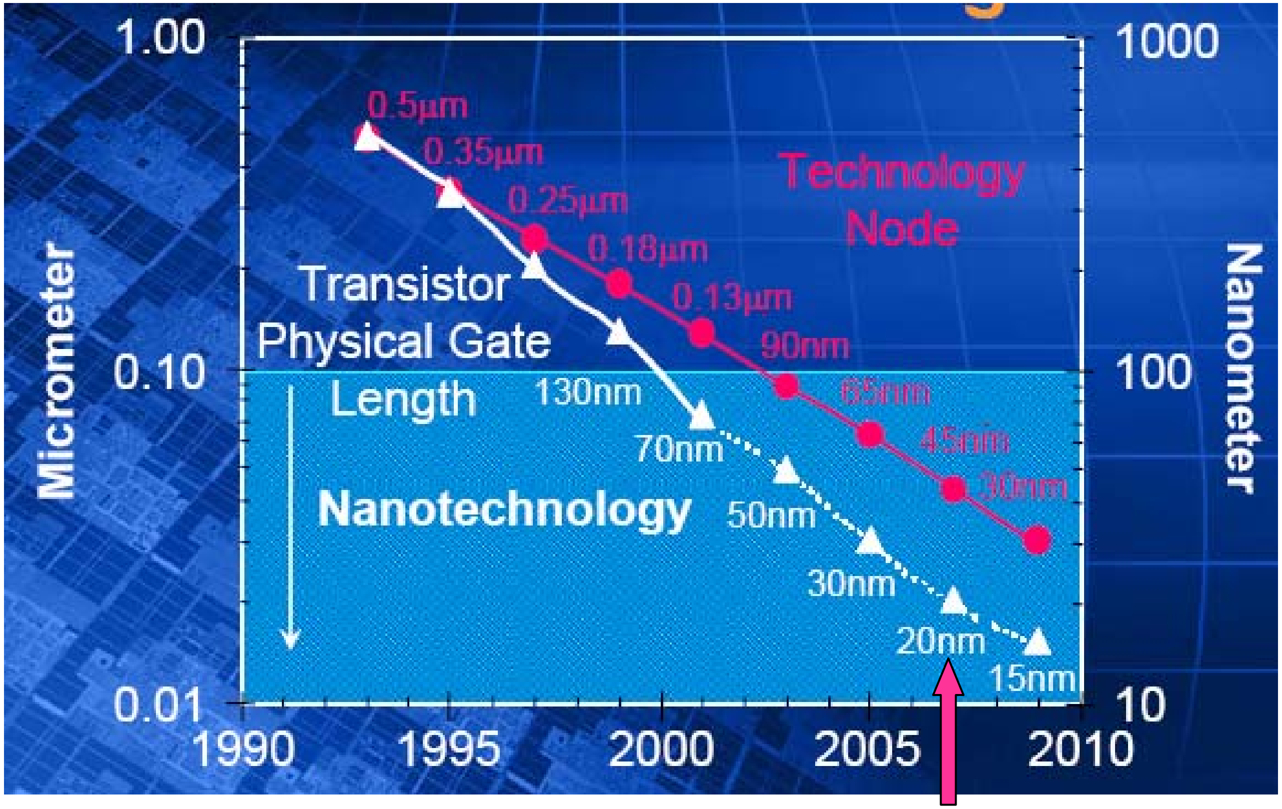
- Doping of Si with rare earth metals
- Tailoring magnetic thin films
- Radio-activated medical implants
- ………

Ion tracks

Single ion events

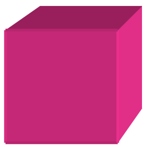
Lowest doses

Physical Limits to Silicon - CMOS Device Scale Down



Moore´s Law

K. David, Intel (2004)



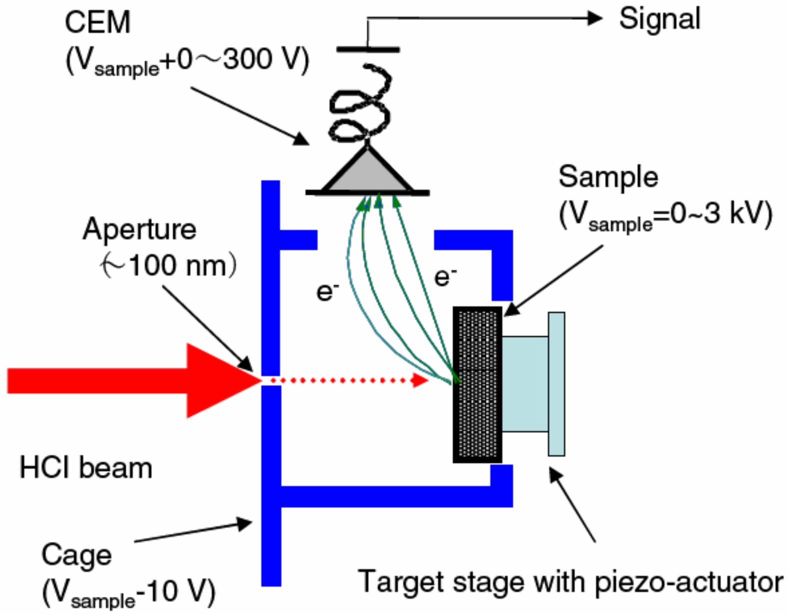
(20 nm)^3: 4 x 10^5 Si-atoms

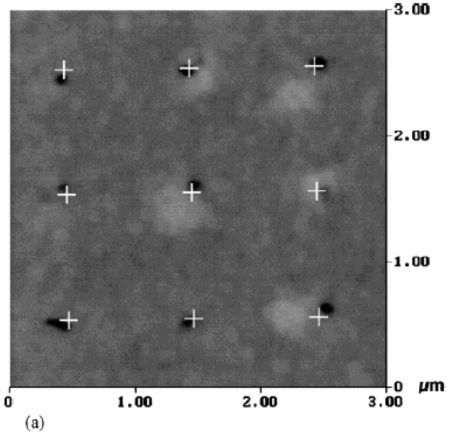
\+ 80 P-atoms

\-------------------------

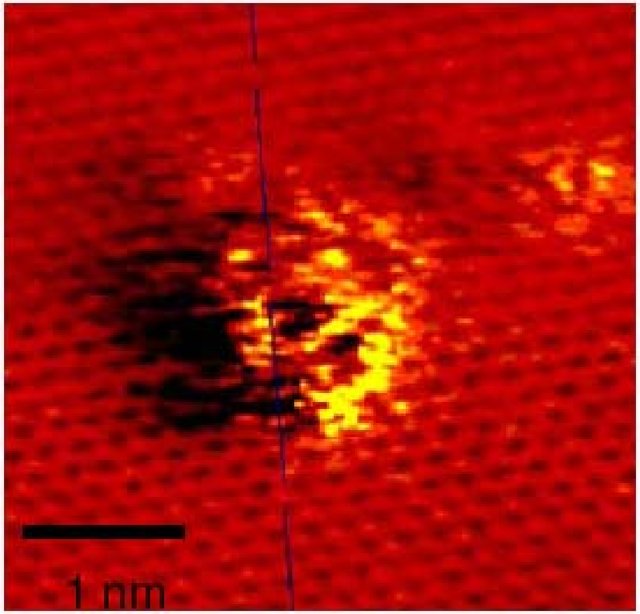
Degeneration

Attempts towards single ion implantations





STM image of a Xe $^{22+}$ impact site on a HOPG surface.

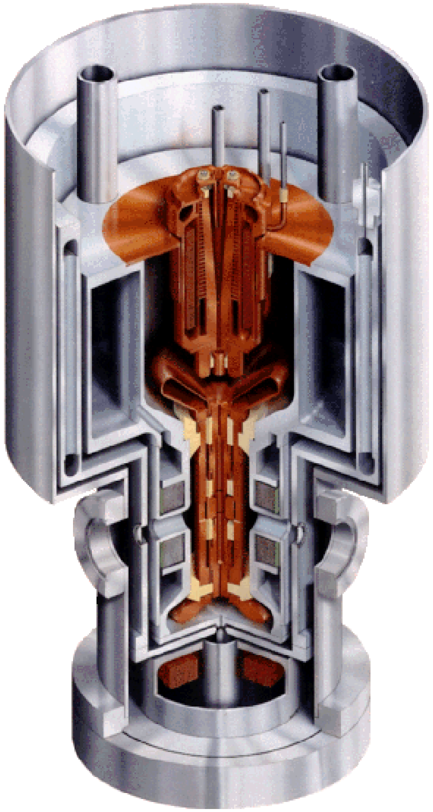


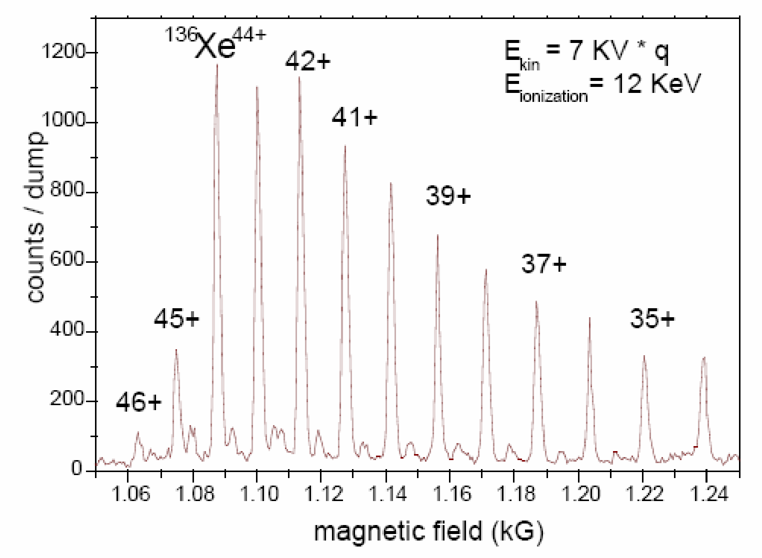
M. Tona, S. Takahashi, J. Phys. Conf. Ser. **2** (2004) 57

Focused Ion Beam Etched Hole Pattern for SII masks

T. Shinda et al., JJAP 41 (2002) L 287

Highly Charged Ions from Electron Beam Ion Trap (EBIT) at LBNL

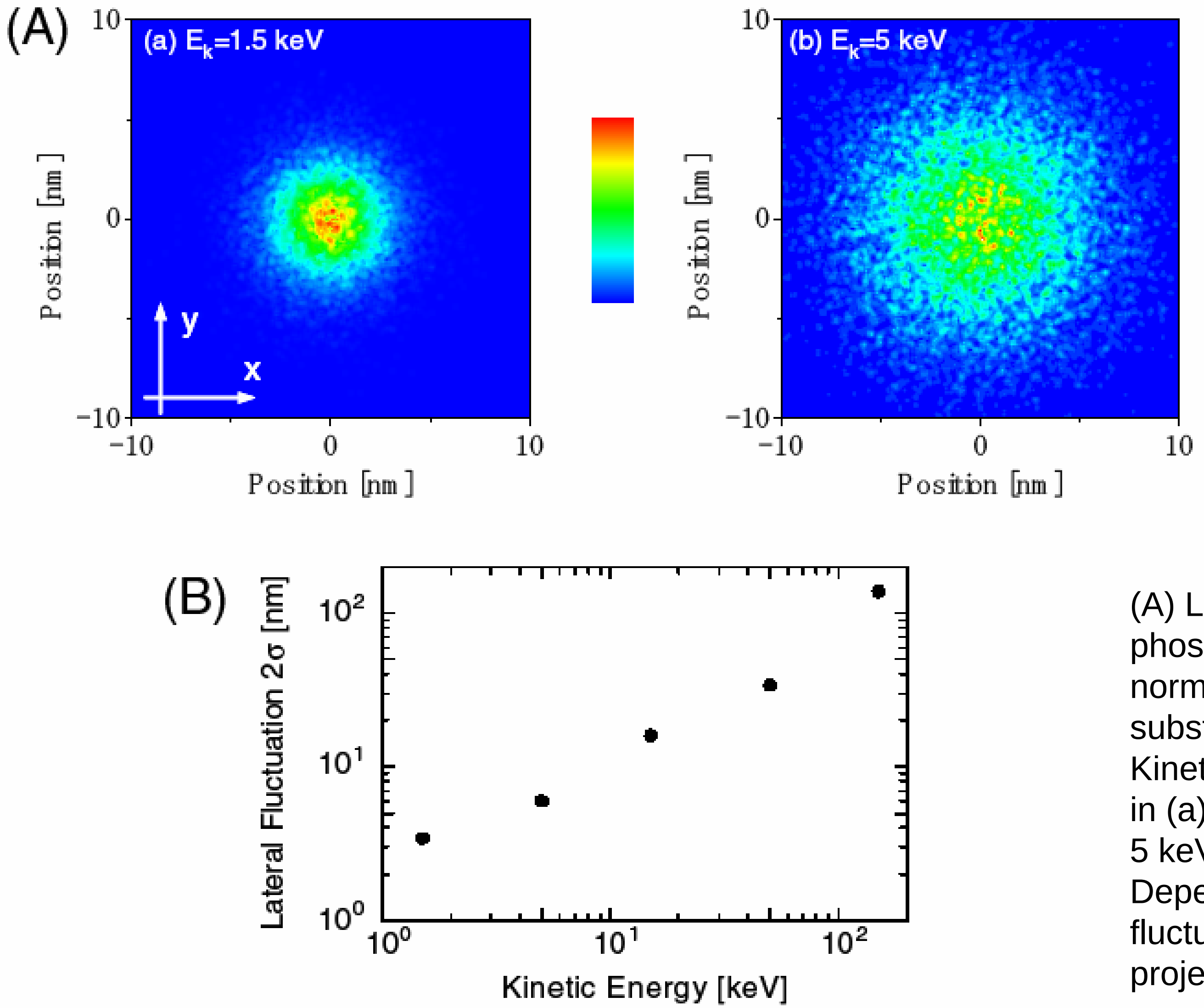




T.Schenkel, LBNL (2003)

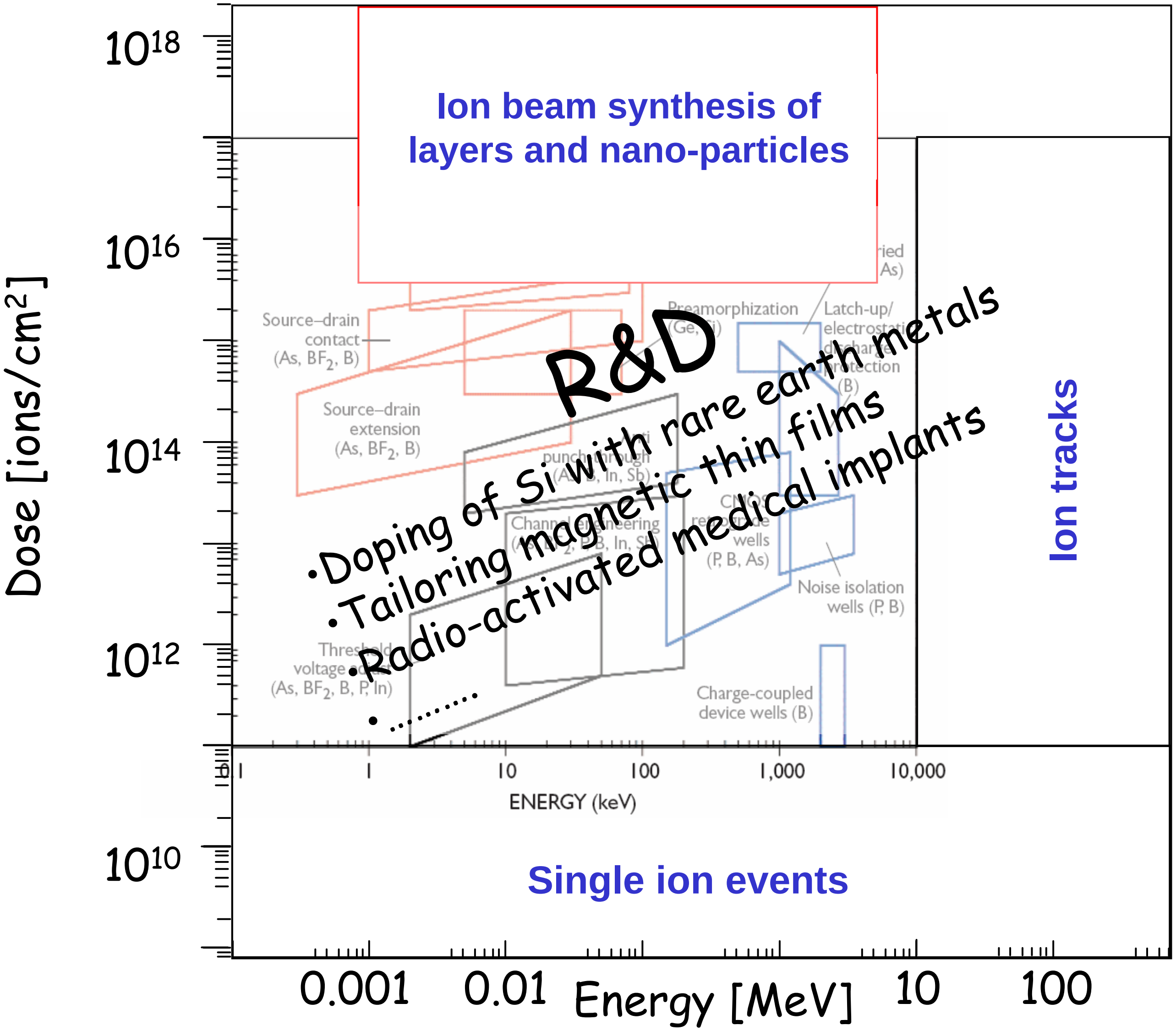
Energy requirements in future single ion implants

M. Tona, S. Takahashi, J. of Phys. Conf. Ser. **2** (2004) 57



(A) Lateral distribution of phosphorus ions when they are normally implanted into Si substrate (simulated results). Kinetic energy of the projectiles in (a) and in (b) are 1.5 keV and 5 keV, respectively. (B) Dependence of positional fluctuation on kinetic energy of projectiles.

Application of Ion Implantation in Semiconductor Industries and Research



Ion beam synthesis of layers and nano-particles

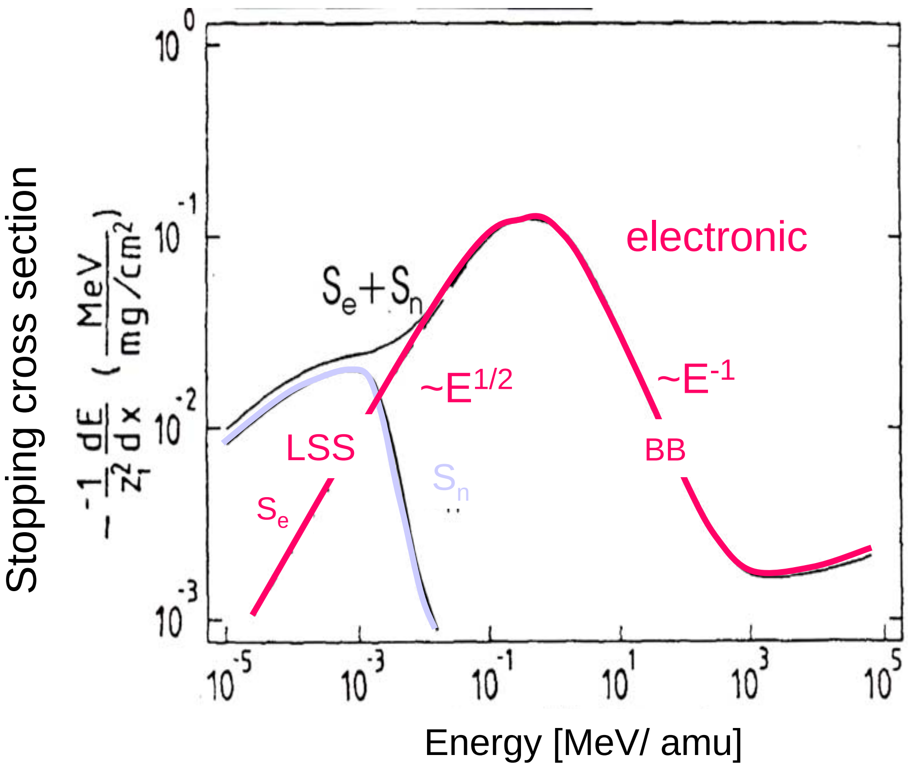
R&D

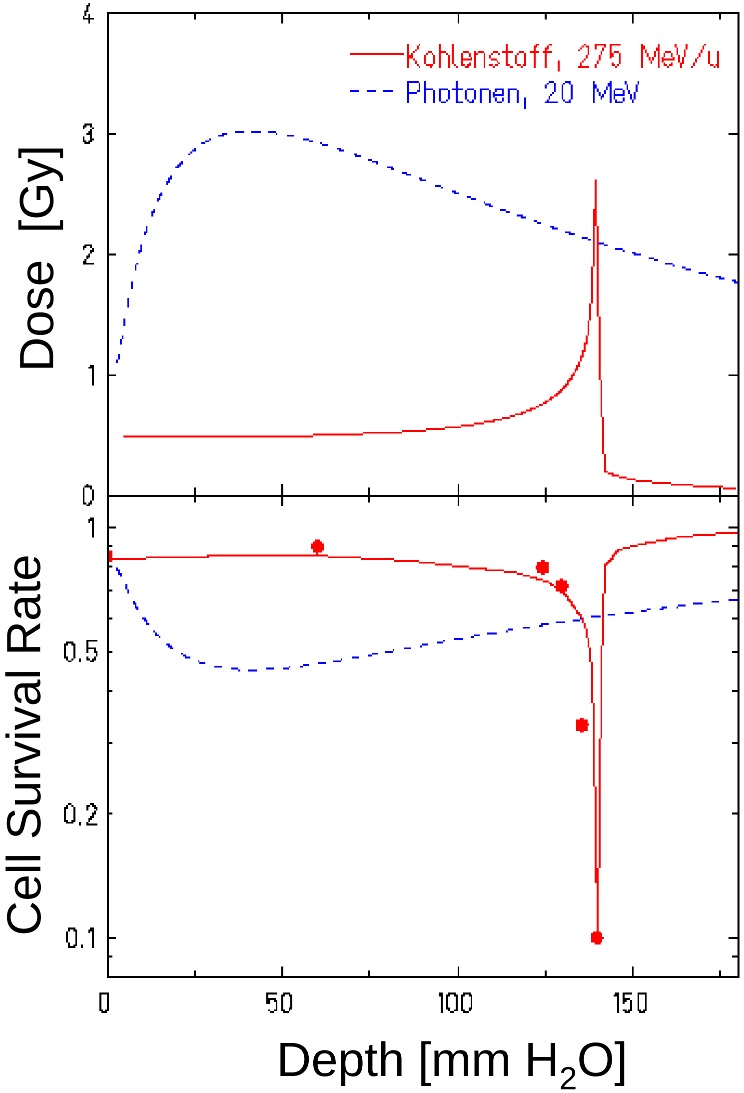
- Doping of Si with rare earth metals
- Tailoring magnetic thin films
- Radio-activated medical implants
- ………

Ion tracks

Single ion events

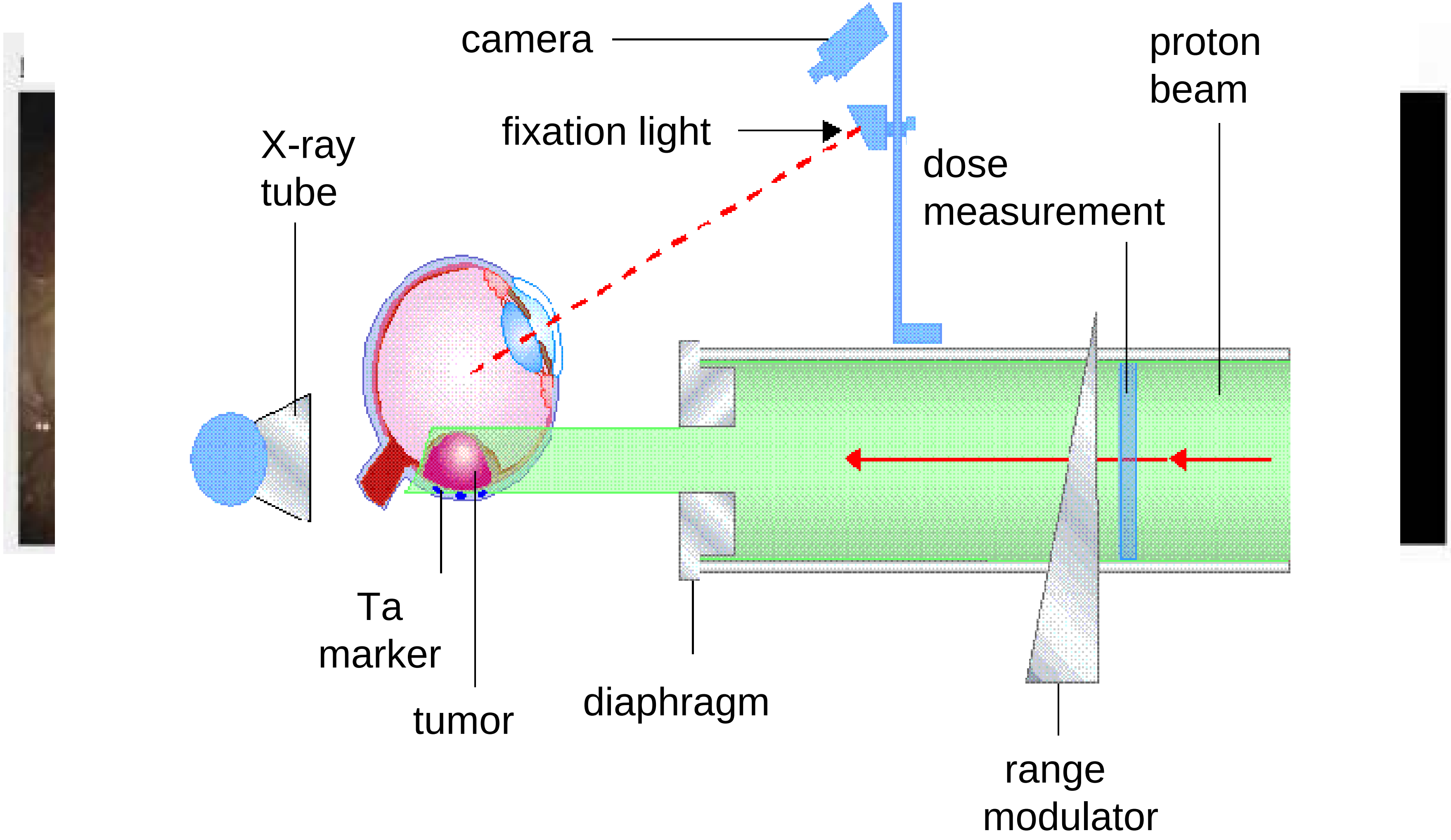
Tumor Therapy with Ions





source: GSI Darmstadt

Eye cancer treatment at Hahn-Meitner-Institute HMI Berlin with Protons



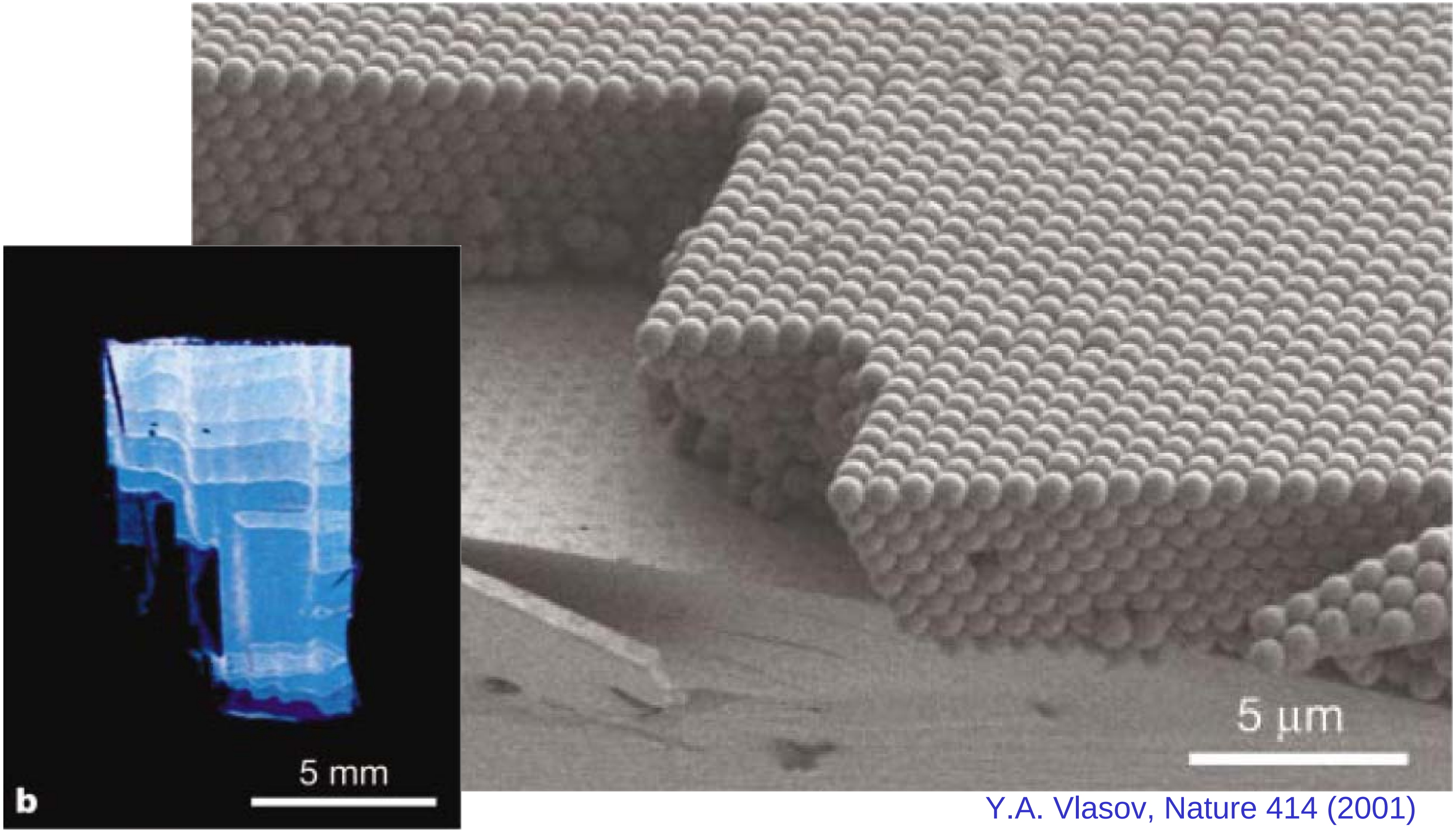
Images: http://www.hmi.de/isl/att/

WWW-Links: http://www.eyecancer.com/, http://www.uni-essen.de/augenklinik/if/infoahmm.html

- Colloids

Self-Assembled Colloidal Crystal

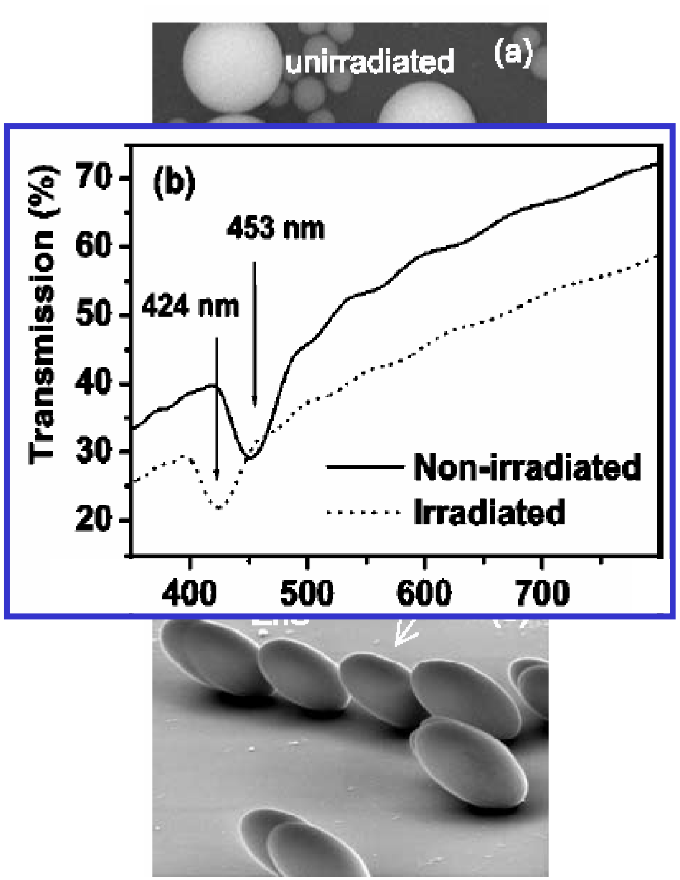
Template for an photonic bandgap crystal



Y.A. Vlasov, Nature 414 (2001)

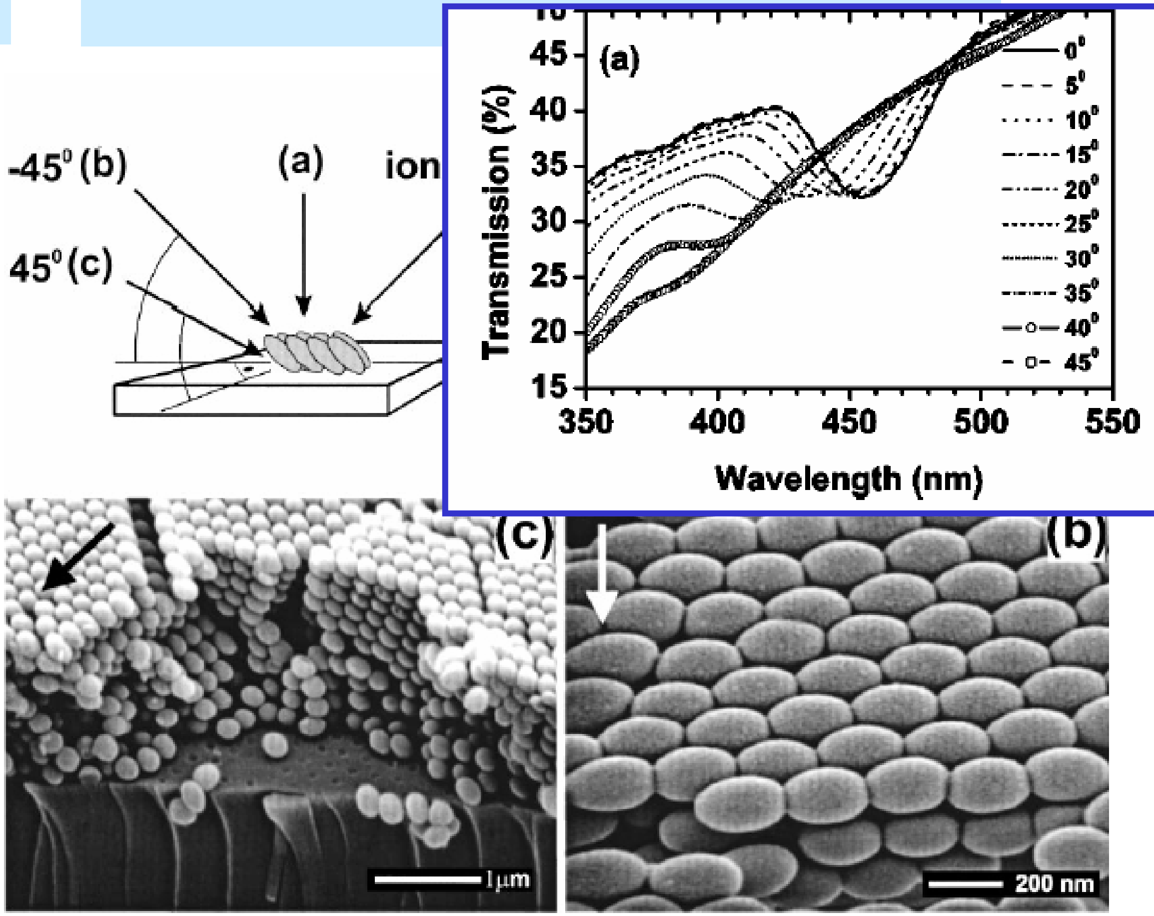
MeV Ion Irradiation of Colloidal Particles and Crystals

4 MeV Xe^{4+} , D = 3 x 10^{14} cm^{-2}
T$_i$ = 90 K, R$_p$(SiO$_2$) = 1.9 µm



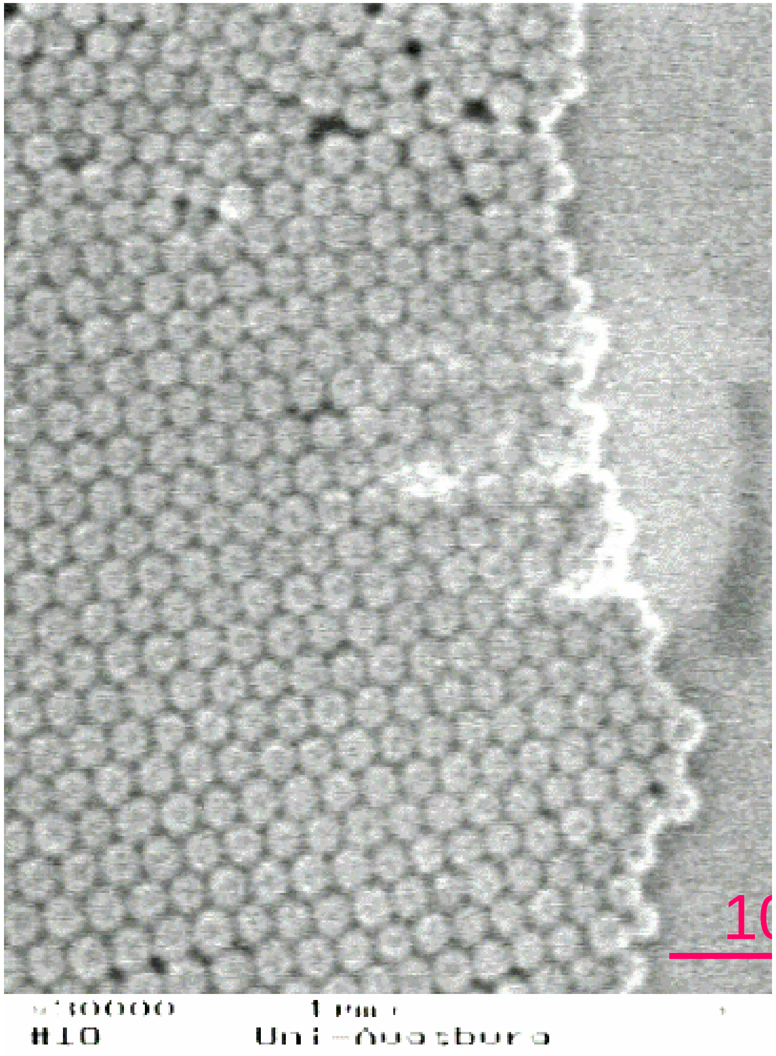
E. Snoeks et al., NIM B 178 (2001) 62

4 MeV Xe^{4+} , D = 1 x 10^{15} cm^{-2}, T$_i$ = 90 K

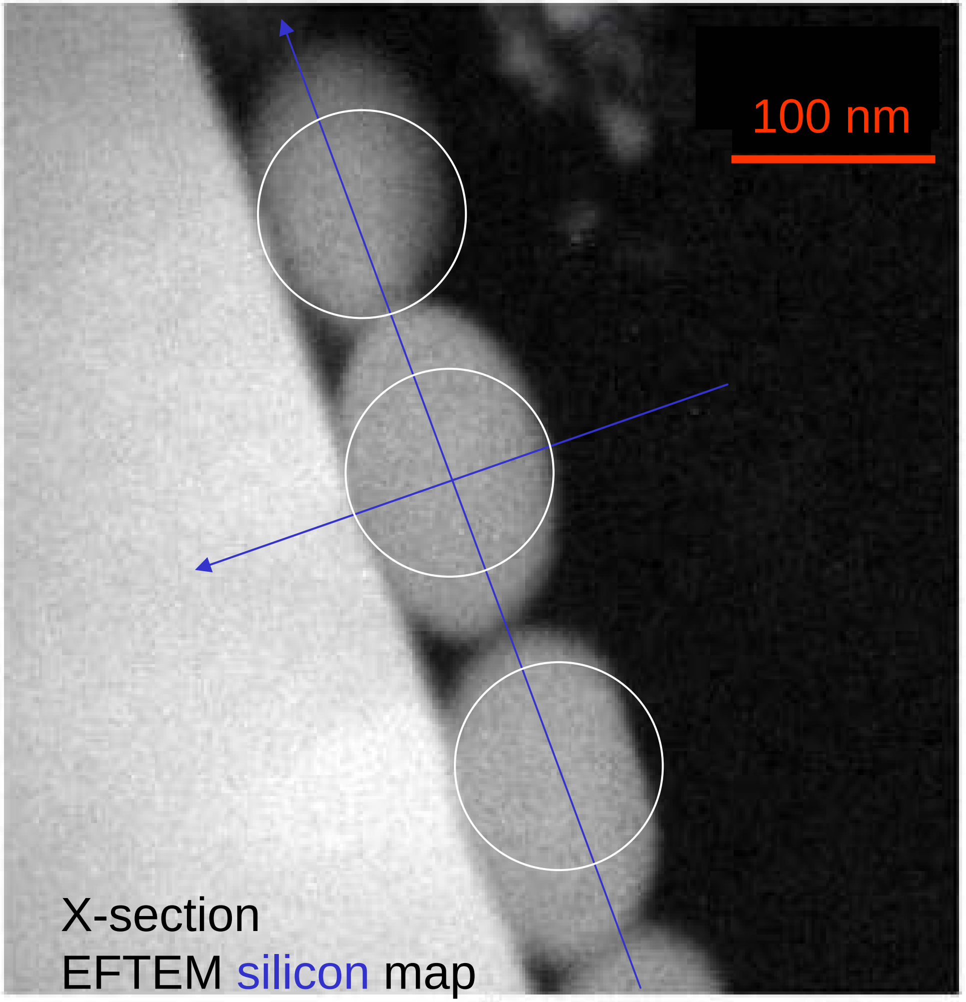


K.P. Velikov et al., APL81 (2002)

Colloidal Nanomasks

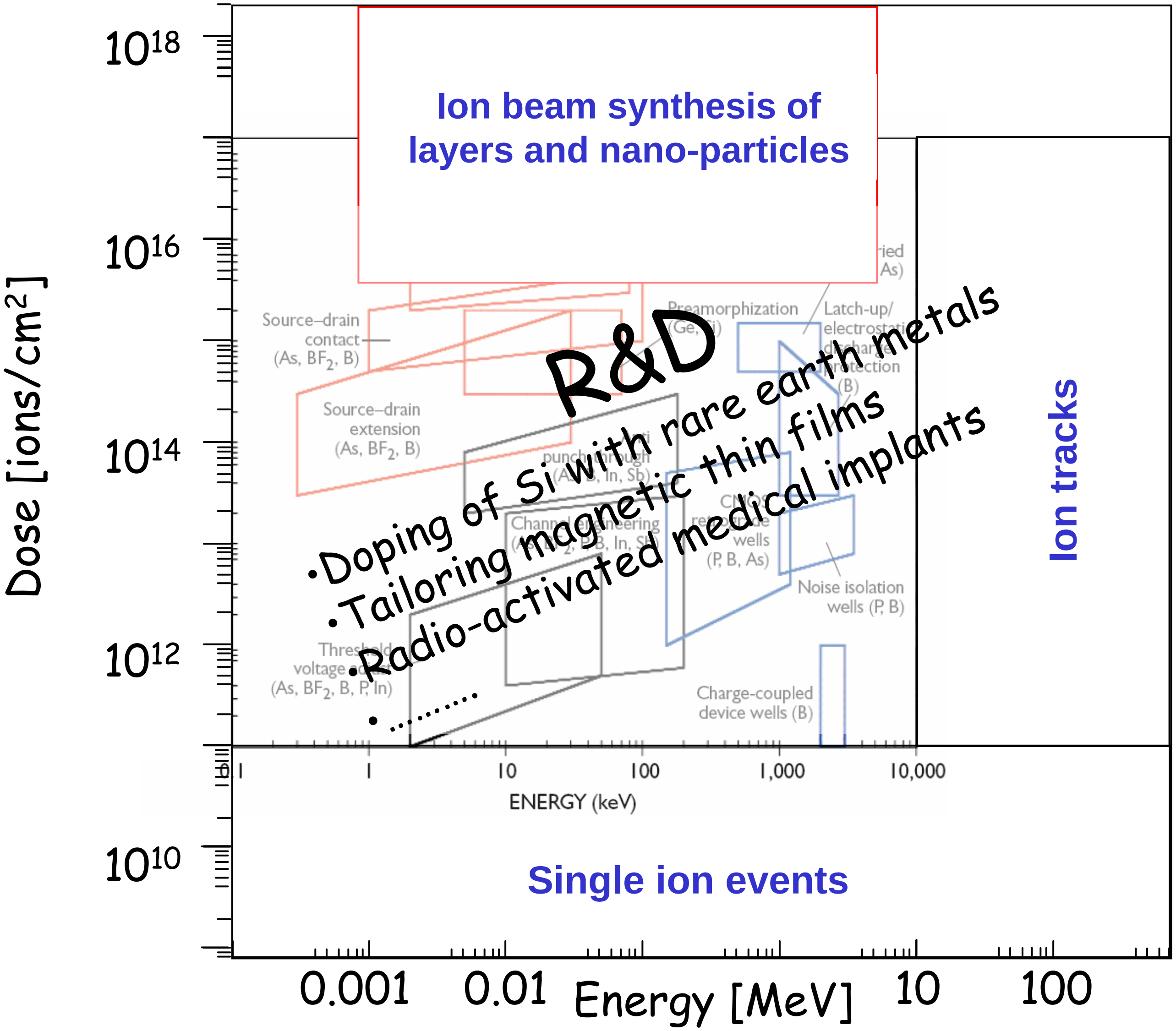


75 keV C^+ Ions , $D = 3.3 \times 10^{16}$ C/cm^2, T_i = RT



X-section
EFTEM silicon map

Application of Ion Implantation in Semiconductor Industries and Research



Ion beam synthesis of layers and nano-particles

R&D

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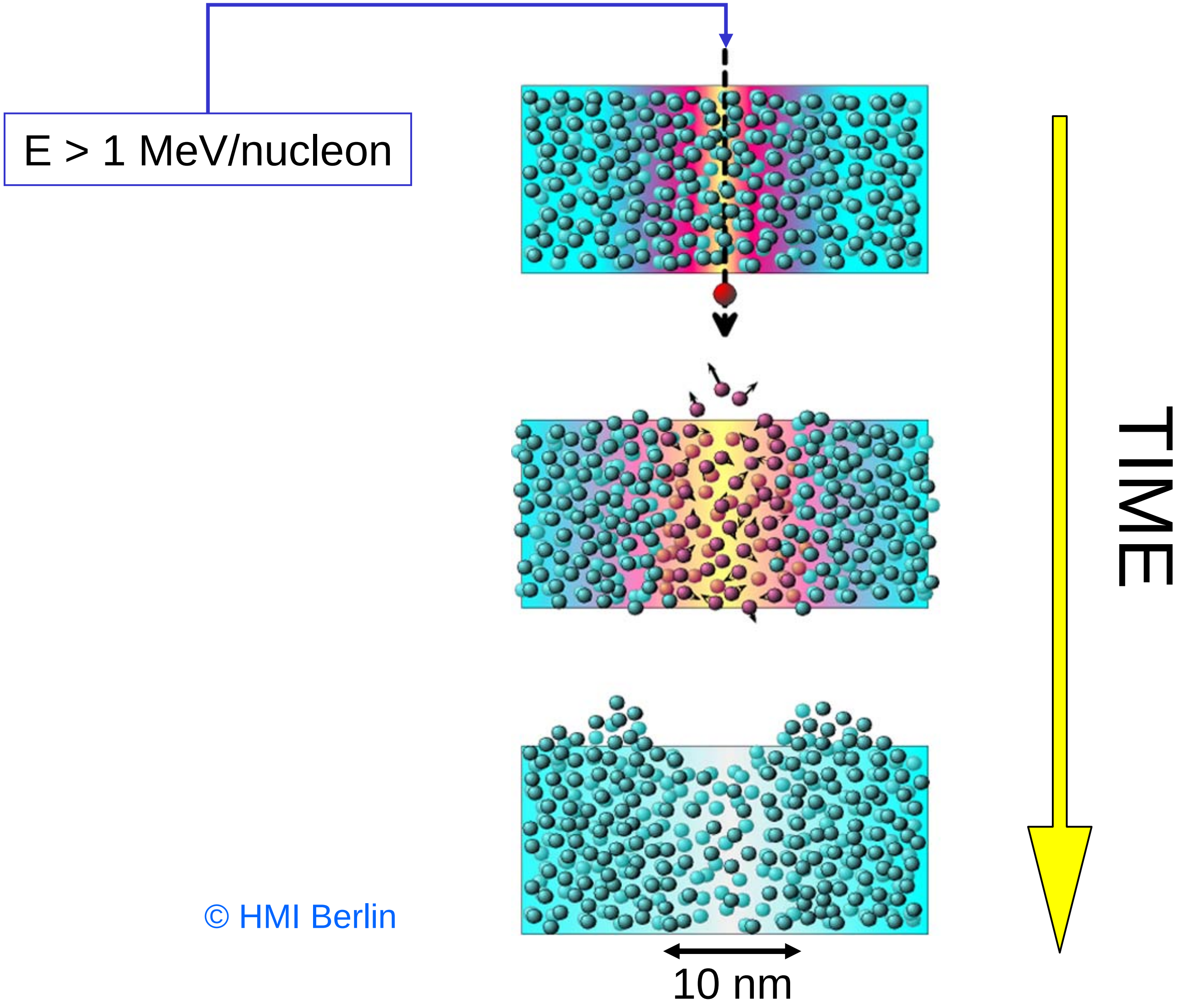
- ……….

Ion tracks

Single ion events

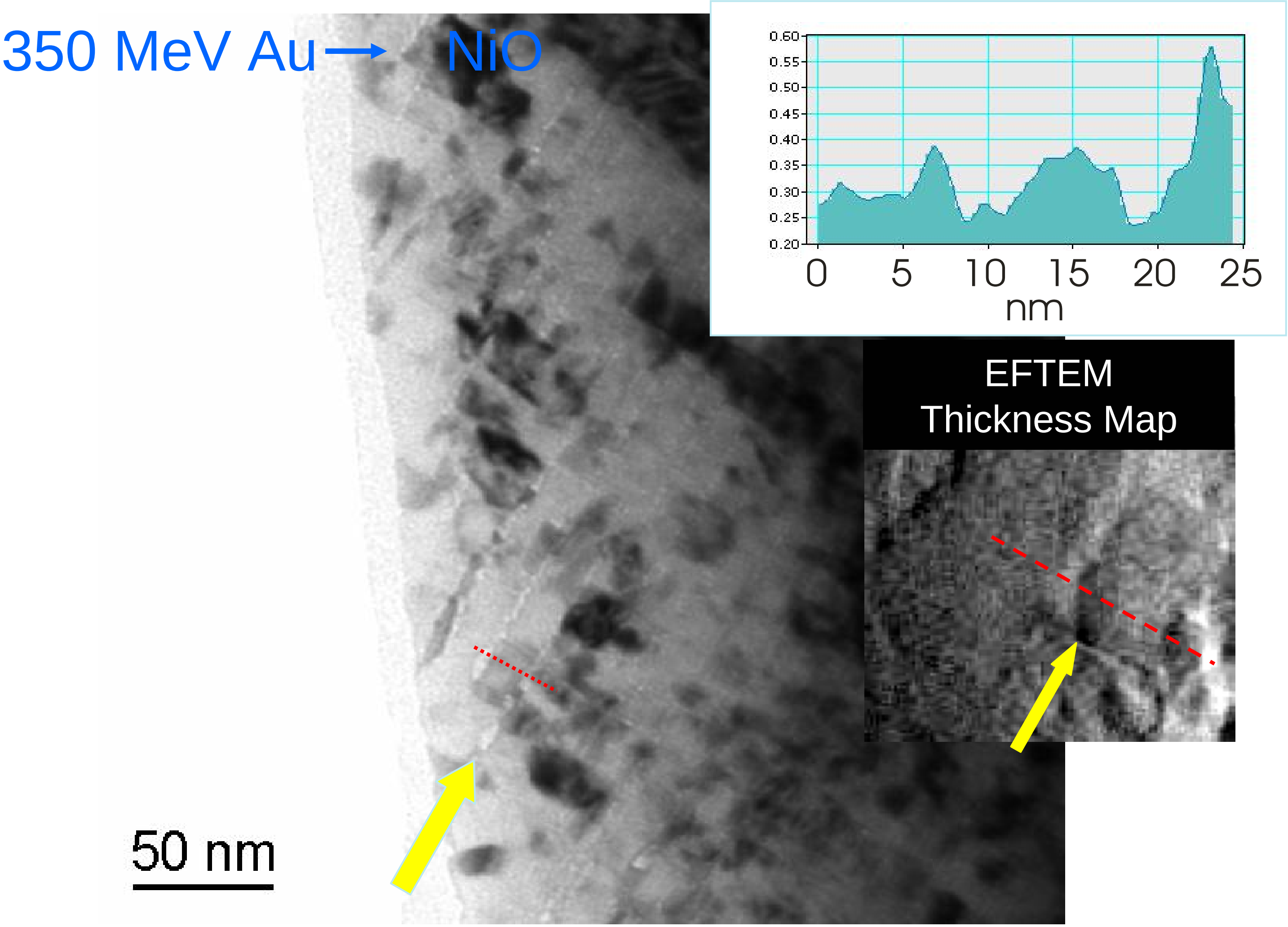
Ion Tracks



E > 1 MeV/nucleon

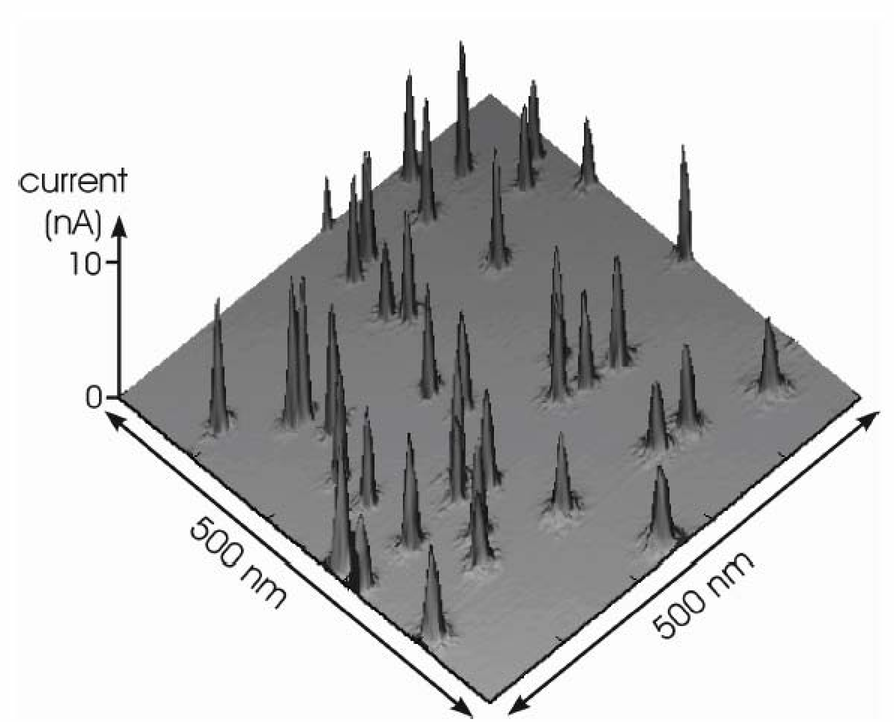
© HMI Berlin

Direct Evidence of Reduced Densities in Single Ion Tracks

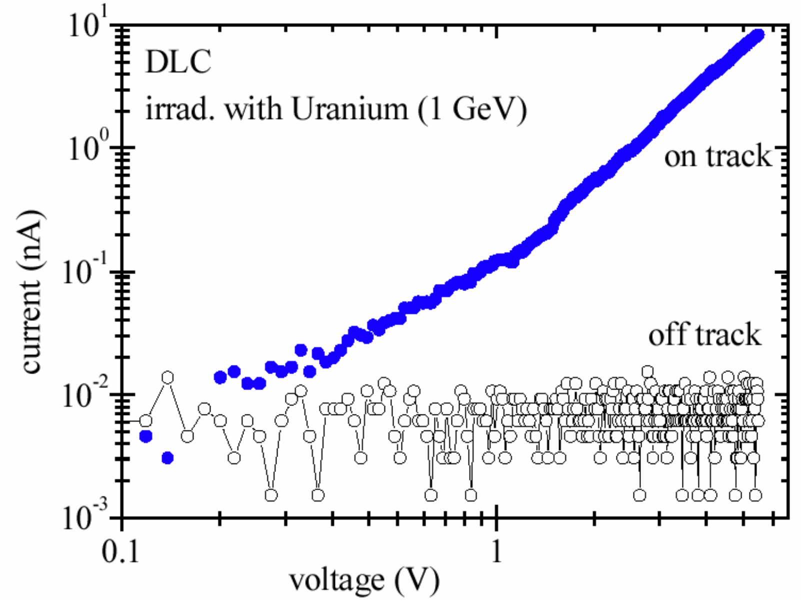


In collaboration with Ch. Dais, W. Bolse, Uni Stuttgart

Ion Tracks: Graphitization of Diamond-like Carbon



Current image of a DLC film, 100 nm thick, irradiated with 10^{10} U/cm^2. Current measurements performed with a conducting AFM tip.



Current/voltage curve for a single ion track (AFM tip on top of a track). For comparison, the corresponding curve for the off track position is shown. DLC film 100 nm thick.

A. Weidinger et al. (2003)

Fe single crystals in etched ion tracks of polymer foils

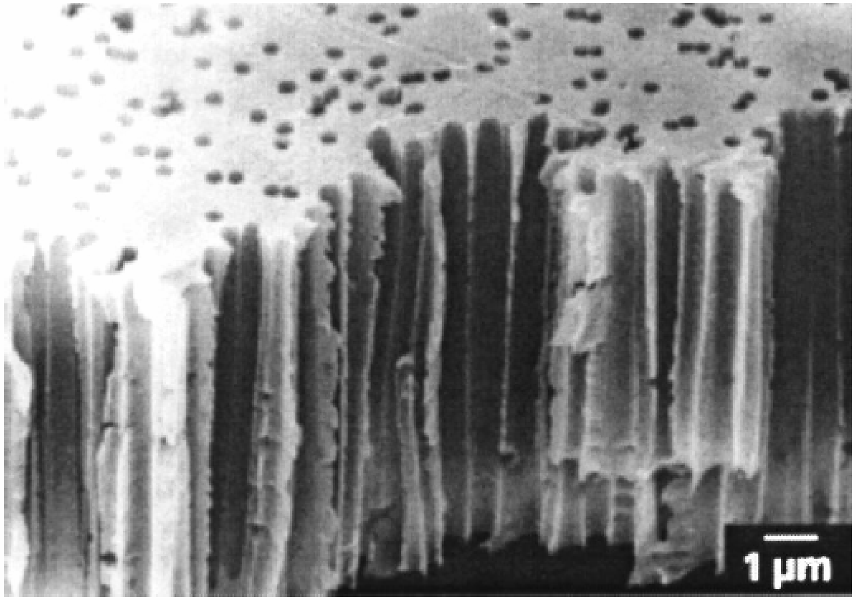
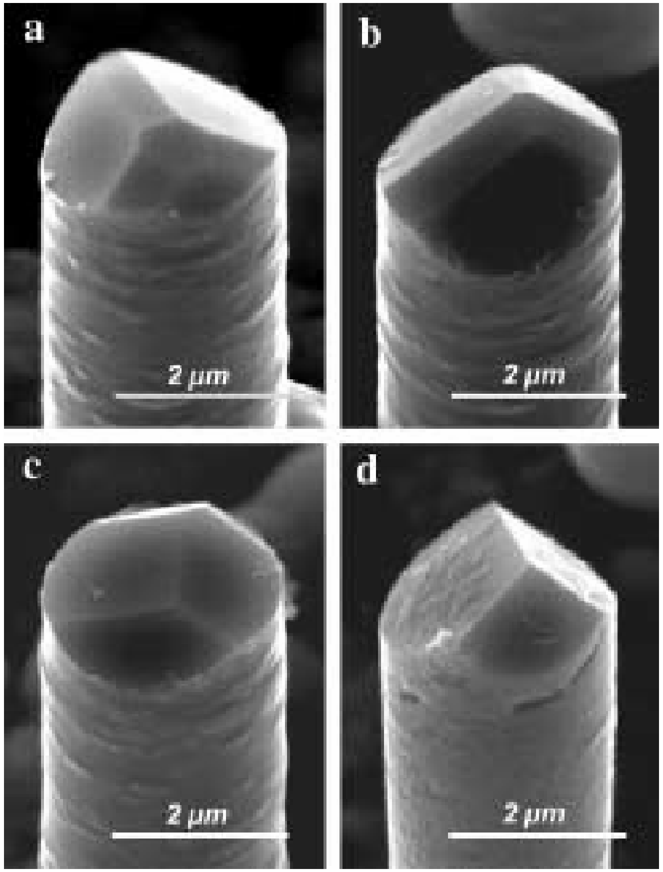


FIG. 1. Scanning electron micrograph of etched ion tracks in PET foil. In the present work the diameter of the tracks is approximately 180 nm, the lateral density was 7×10^7 cm^2.

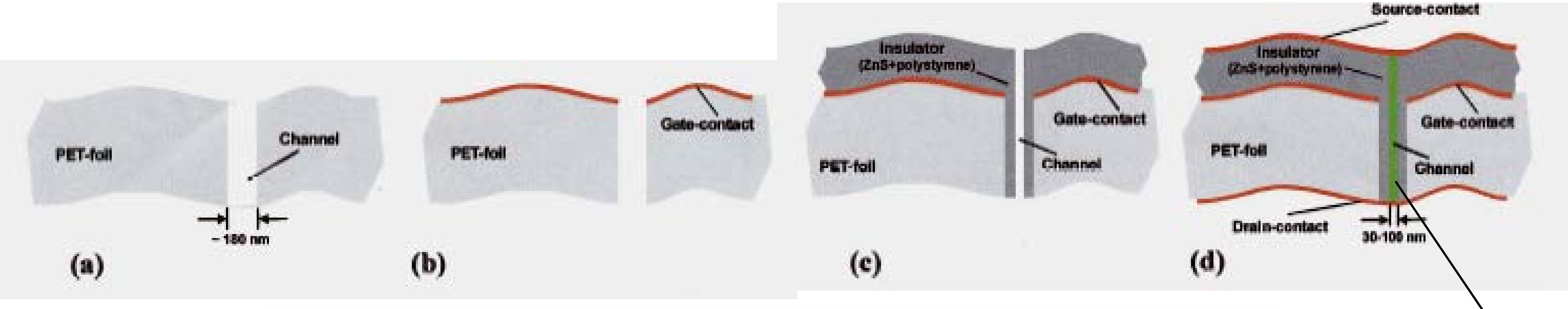
J. Chen et al., APL85 (2004)



Iron single crystals oriented along the [110] crystallographic axis

D. Dobrev et al., Appl. Phys. A 72 (2001) 729

Vertical nanowire transistors



CuSCN

J. Chen et al., APL85 (2004)

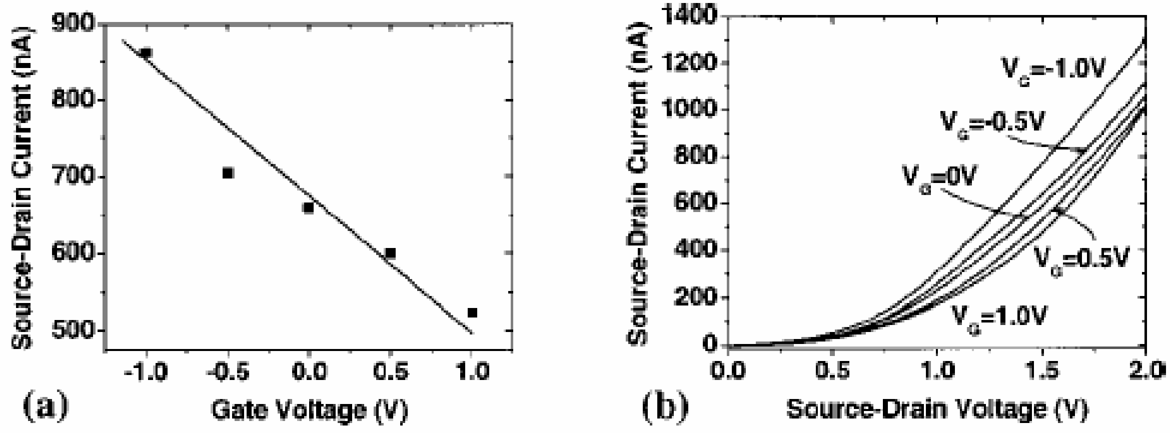
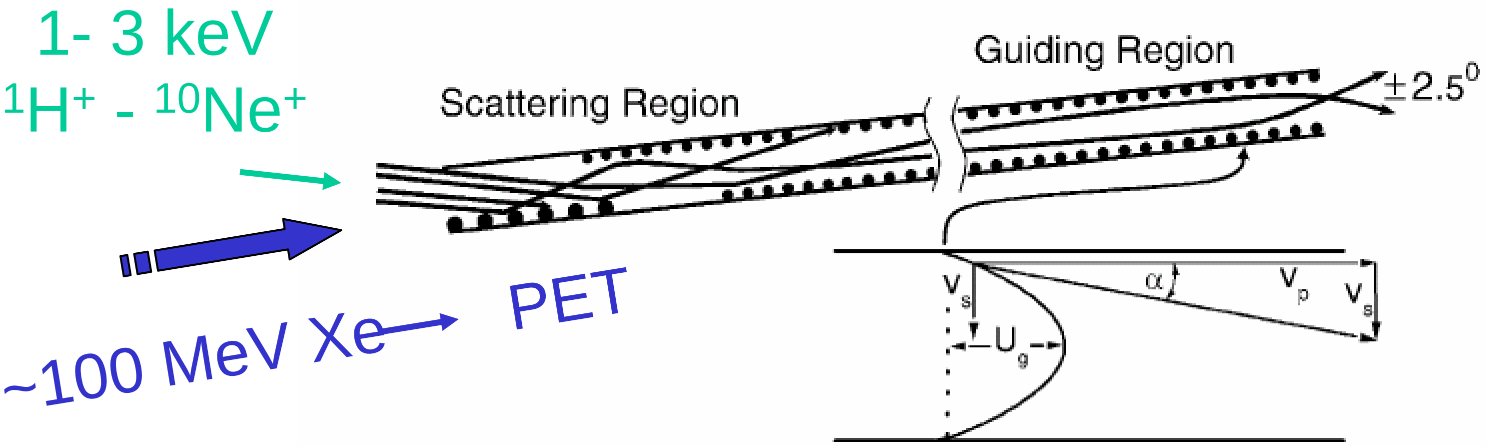


FIG. 3. Electrical characteristic of an array of ~1600 nanowire transistors in polymer foil. (a) Transfer characteristic; the source–drain voltage is 1.6 V. (b) Source–drain characteristics at different gate potentials.

Ion Guiding in Insulating Capillars



1- 3 keV

$^{1}H^{+}$ - $^{10}Ne^{+}$

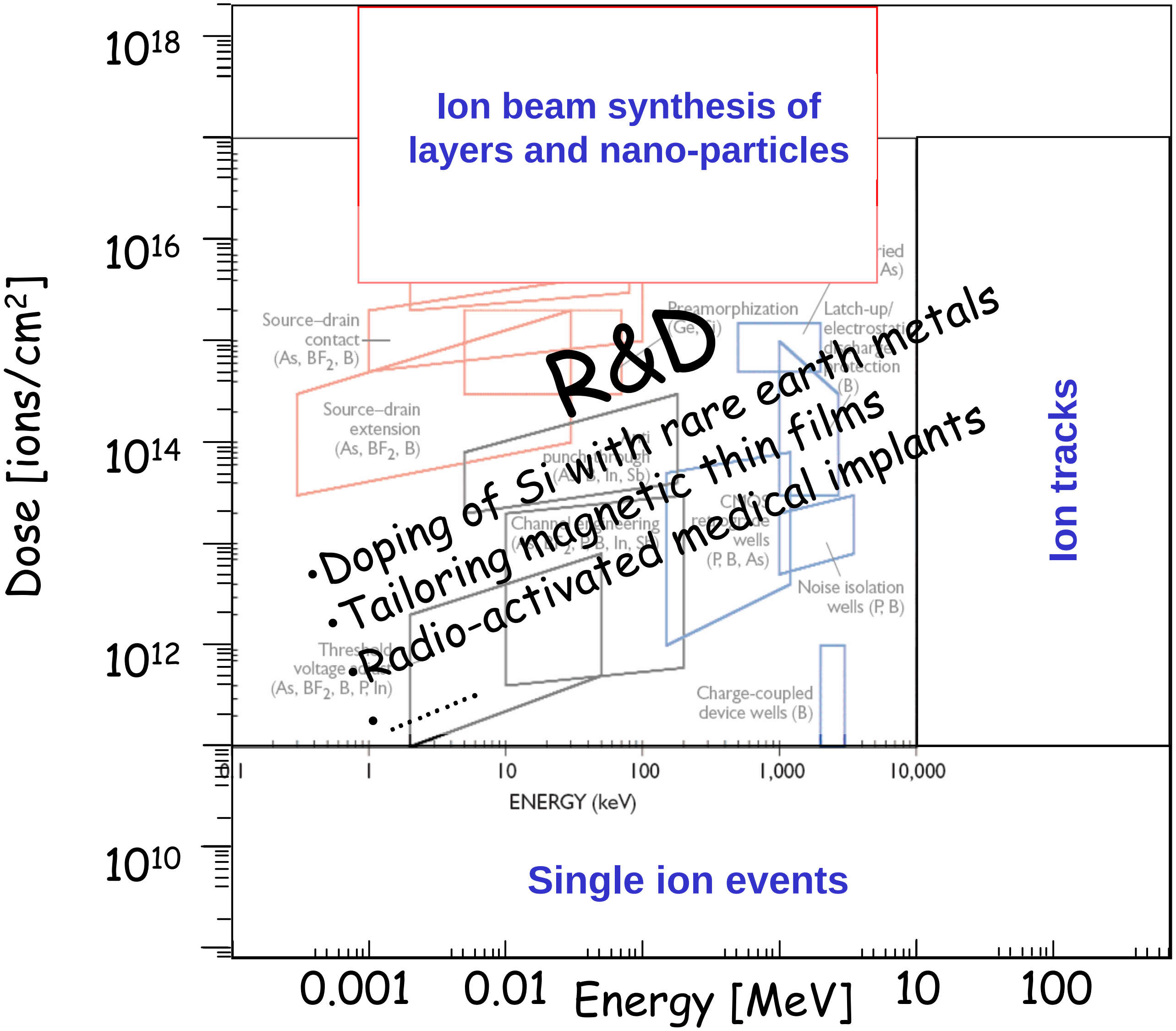
~100 MeV Xe

PET

Fig. 1. Capillary guiding of highly charged ions in a PET capillary. A scattering region and a guiding region are considered to explain characteristic features of the guiding (see text). The guiding region is affected by a potential of depth U_g wherein the ions are deflected if their perpendicular energy $E_\perp$ does not exceed the value of $q_f U_g$, where q_f is the final charge state of the ion.

N. Stolterfoht et al., NIMB 255 (2004)

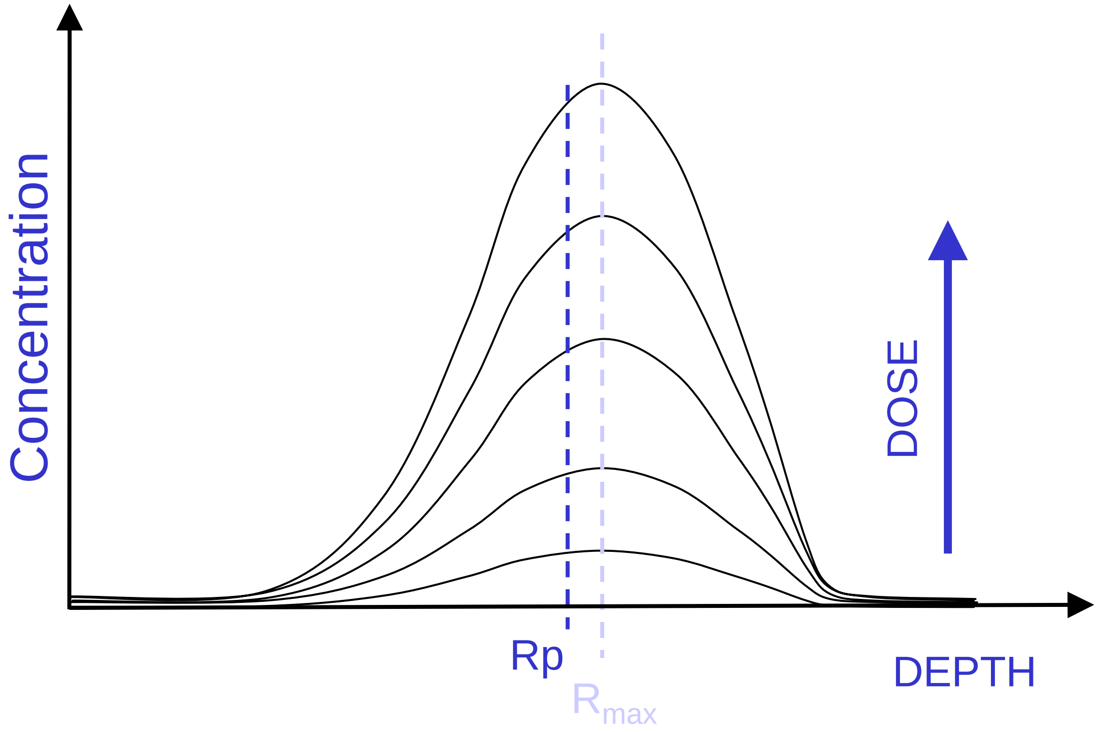
Application of Ion Implantation in Semiconductor Industries and Research



- Doping of Si with rare earth metals
- Tailoring magnetic thin films
- Radio-activated medical implants
- ....

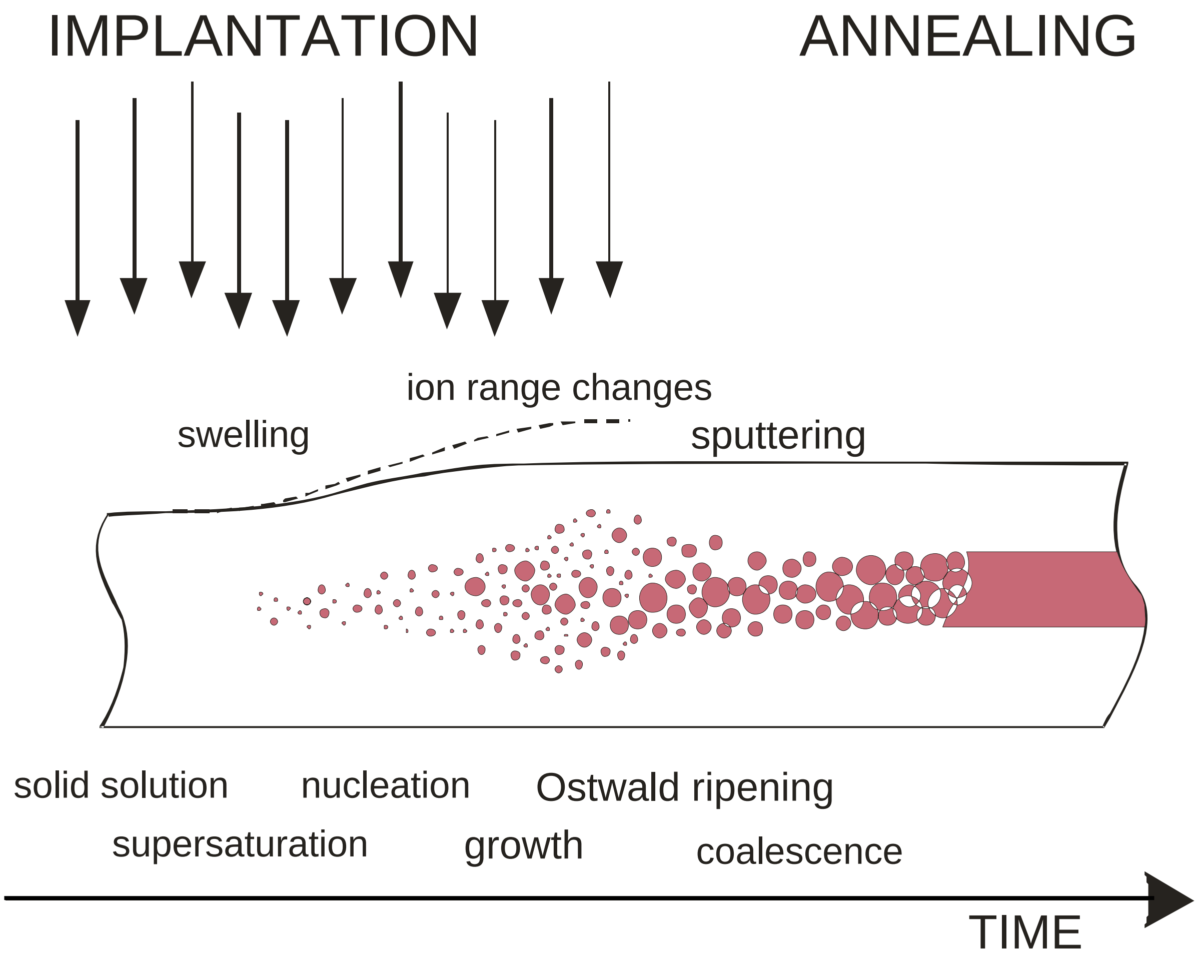
Ion Beam Synthesis of Precipitate Layers and Homogeneous Layers

Ion-Implantation: Ion Profiles



IBS-Schema.cdr

ION BEAM SYNTHESIS



IMPLANTATION

ANNEALING

ion range changes

swelling

sputtering

solid solution

supersaturation

nucleation

growth

Ostwald ripening

coalescence

TIME

Optical Properties of Metallic Nanoclustes in Insulators

Lustre decorations in the glazes of Medieval and Renaissance Pottery of the Middteranean basin consist of Cu and Ag nanoparticles (5-100 nm) in a glassy matrix

Classical Pottery from Deruta (Italy)

Ag NC´s

Cu NC´s

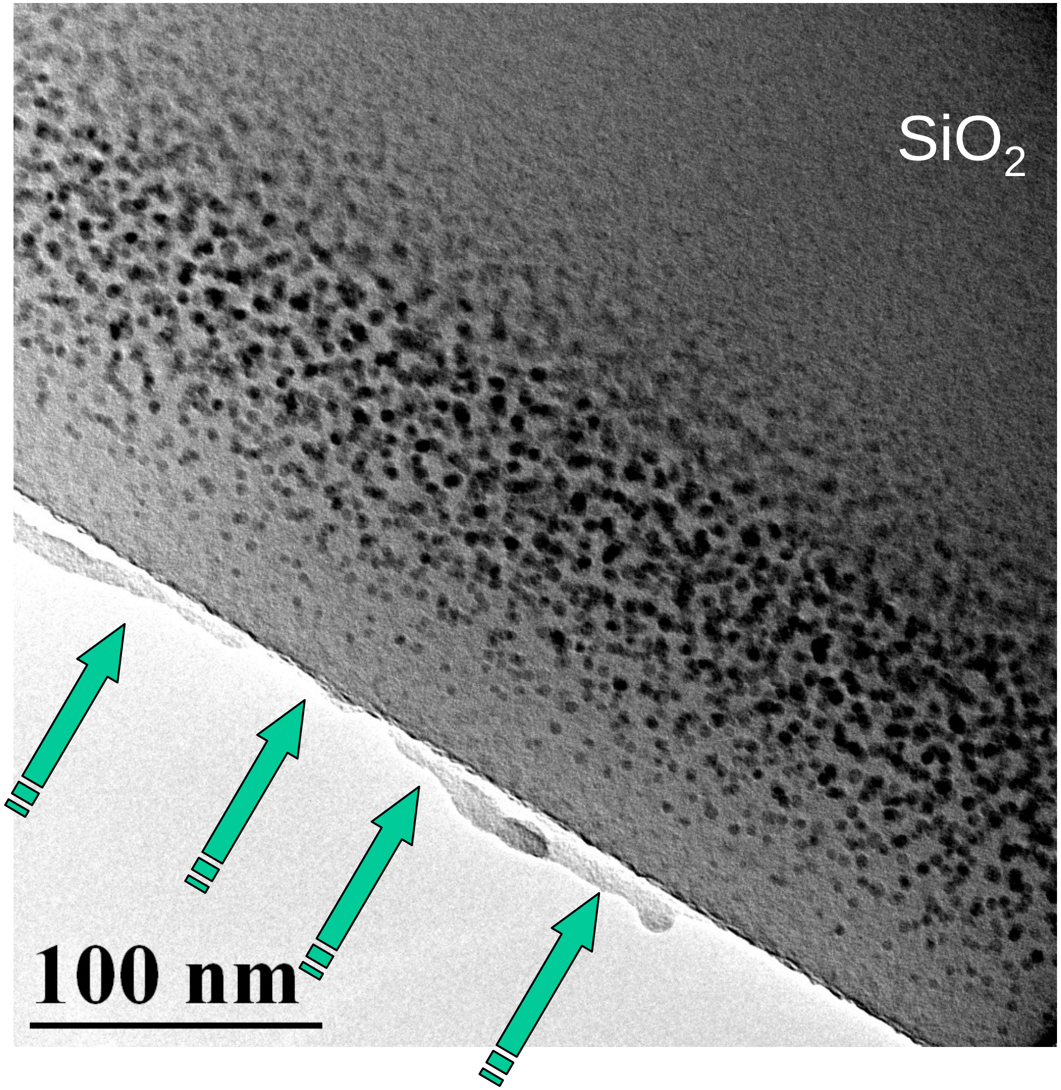
Fidia Deruta m030626-2-f1.jpg

Formation by decomposition of metal salts

S. Padovani et al., J. Appl. Phys. 93 (2003) 10058

Formation of Metallic Nanoparticles in SiO_2

X-sectional
TEM bright-field image



k556 31HF.dm3

surface

120 keV Ni^+

~ 10^{17} Ni/cm^2

Ni in silica glass.cdr

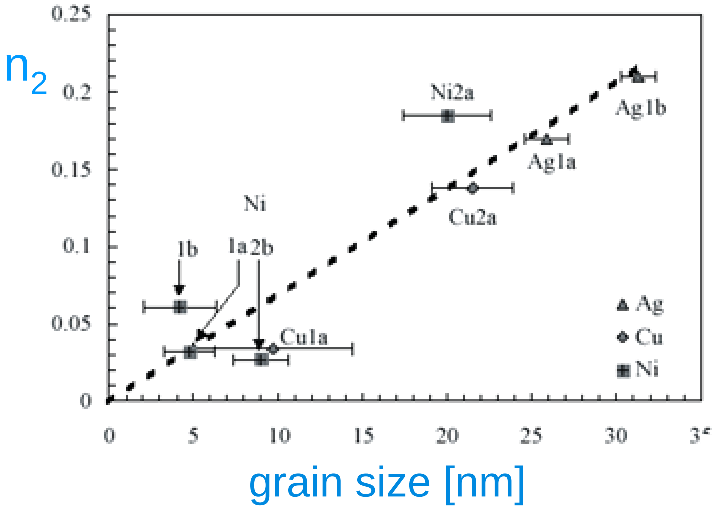
60 kV MEVVA Implantation Ni → Fused Silica Glass

D = 2 x 10^{17} Ni/cm^2, T_i = RT

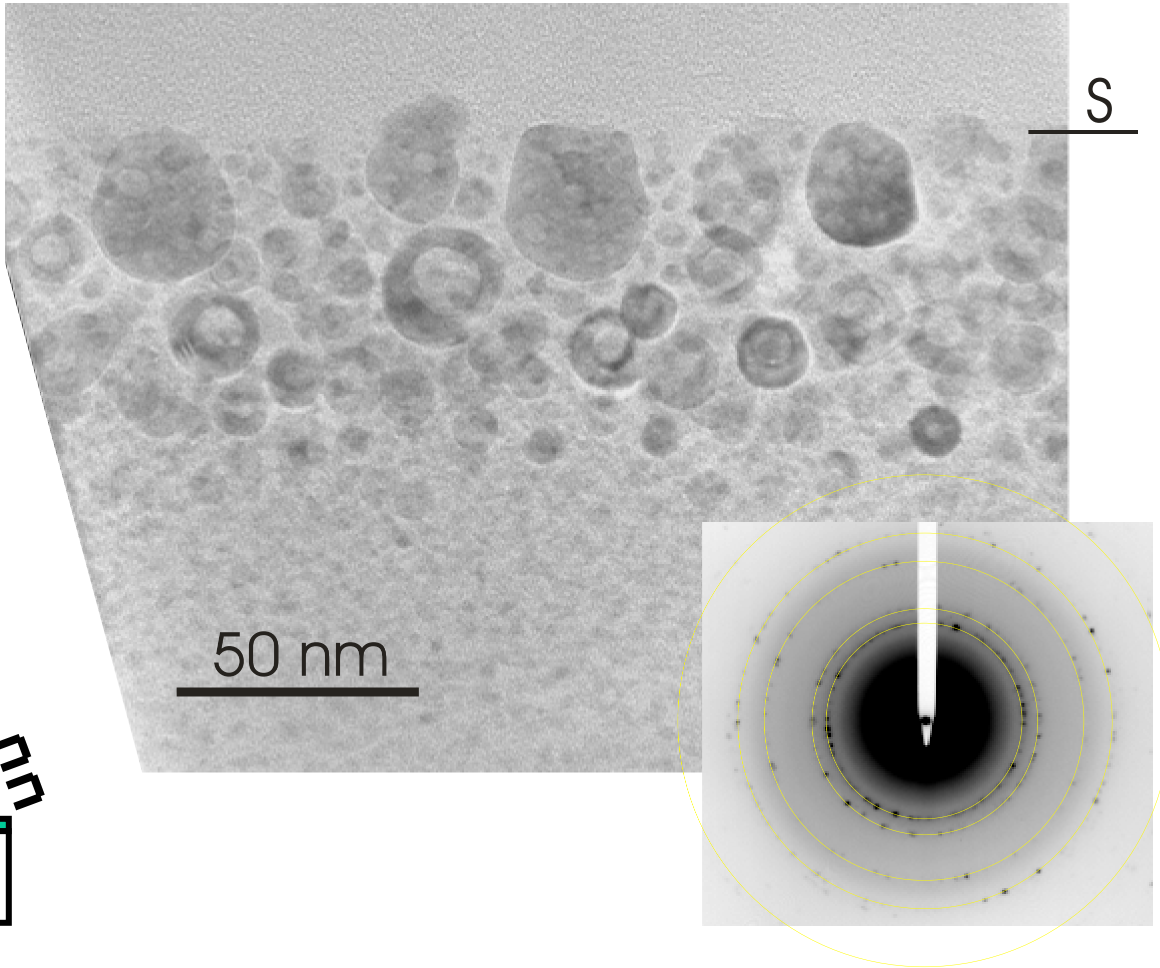
In collaboration with PS Chung & SP Wong, CUHK

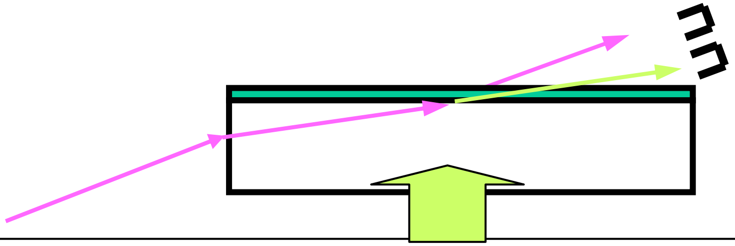
Nonlinear optical constant

$n = n_0 + I\,n_2$



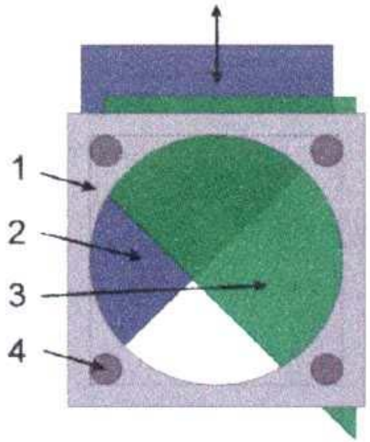
PS Chung, PhD thesis CUHK (2001)





Combinatorial Ion Beam Synthesis of Compound-Nanoclusters

Sequential implantation of keV Cd^+ and Se^+ ions into SiO_2



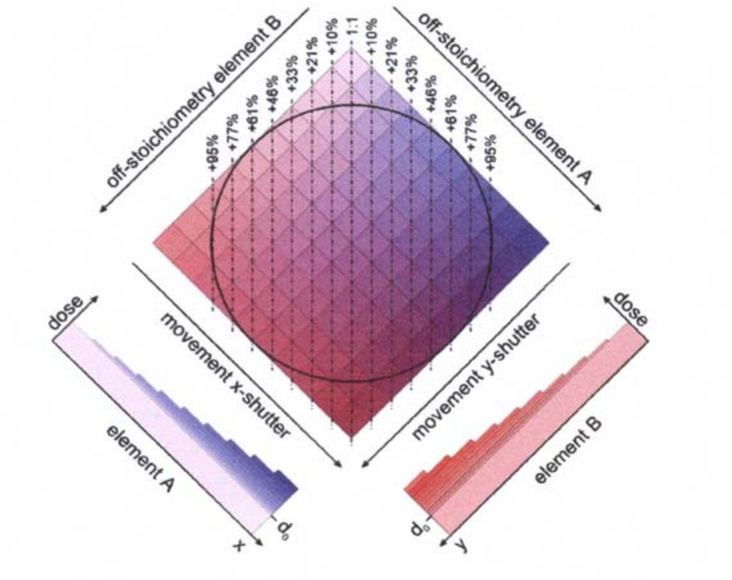


FIGURE 3. Dose profile generated by using the aperture setup of Fig. 2 a) and the parameters a = 1.1 and n = 10.

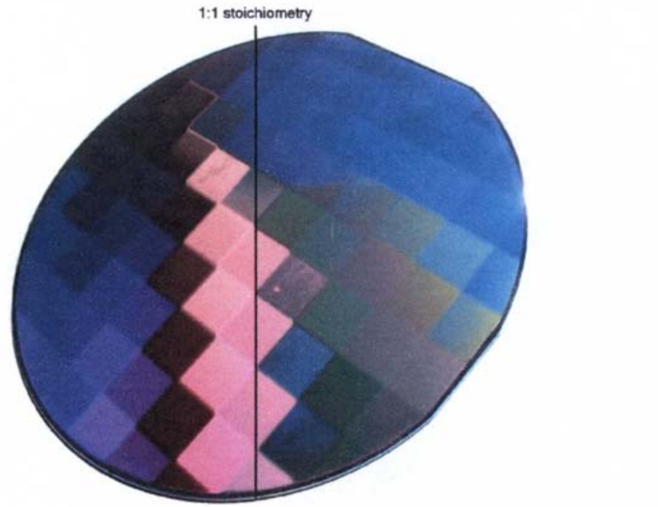


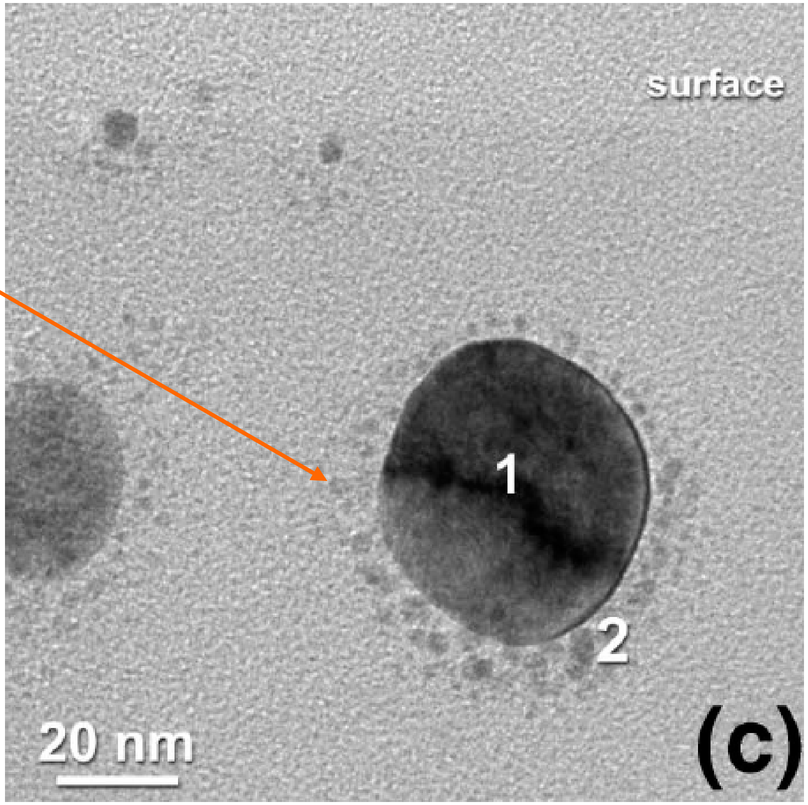
FIGURE 4. Daylight scattered image of a 4-inch Silicon wafer implanted with Cd and Se with the herein discussed parameters and dose d_o of 2.85×10^{16} cm^{-2}.

I. Großhans et al., Proc. CAARI 2002

Adding complexity to Nanoparticles

190 keV Ne^+ , D = 1 x 10^{17} cm^{-2}, RT

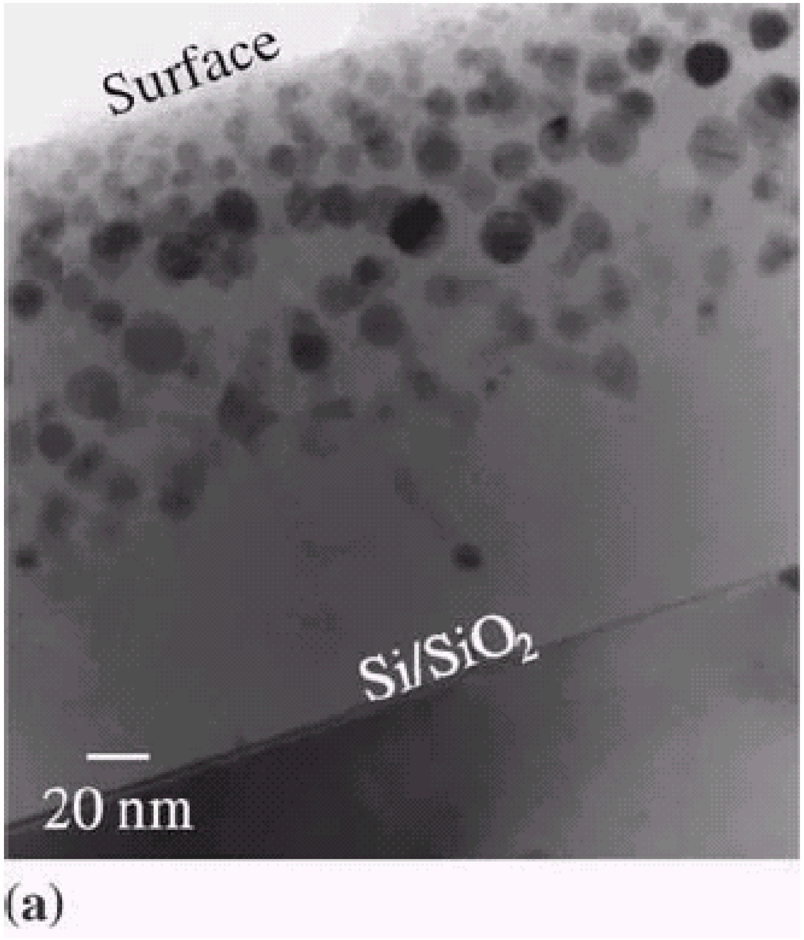
Au-enriched ‘‘satellite’’ nanoparticles around original Au_xCu_{1-x} clusters



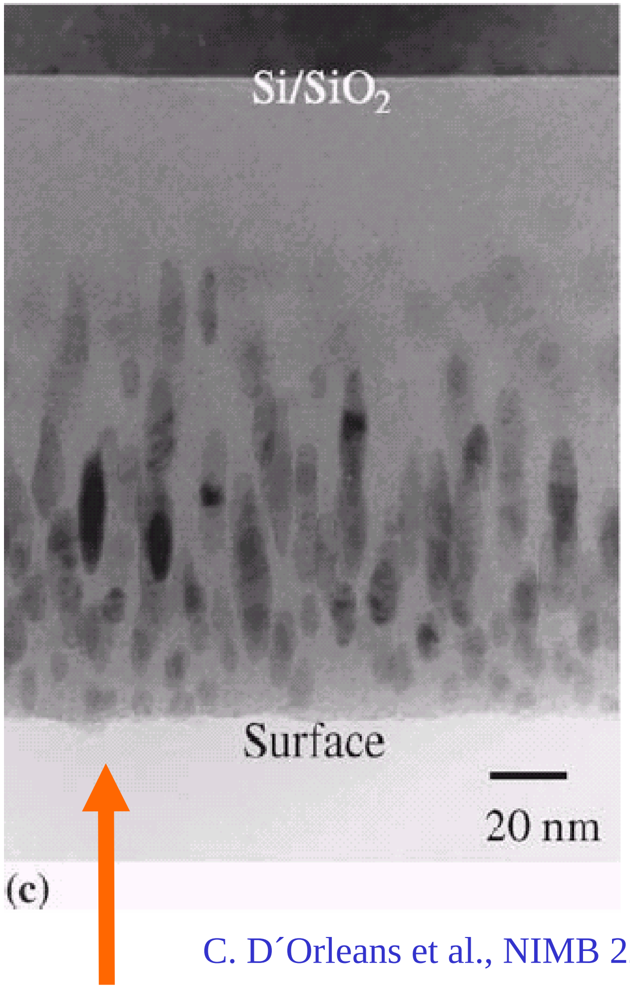
G. Mattei et al., PRL90 (2003)

Deformation of Metallic Nanoparticles in SiO_2

160 keV Co → SiO_2/Si, D = 1 x 10^{17} Co/cm^{-2}

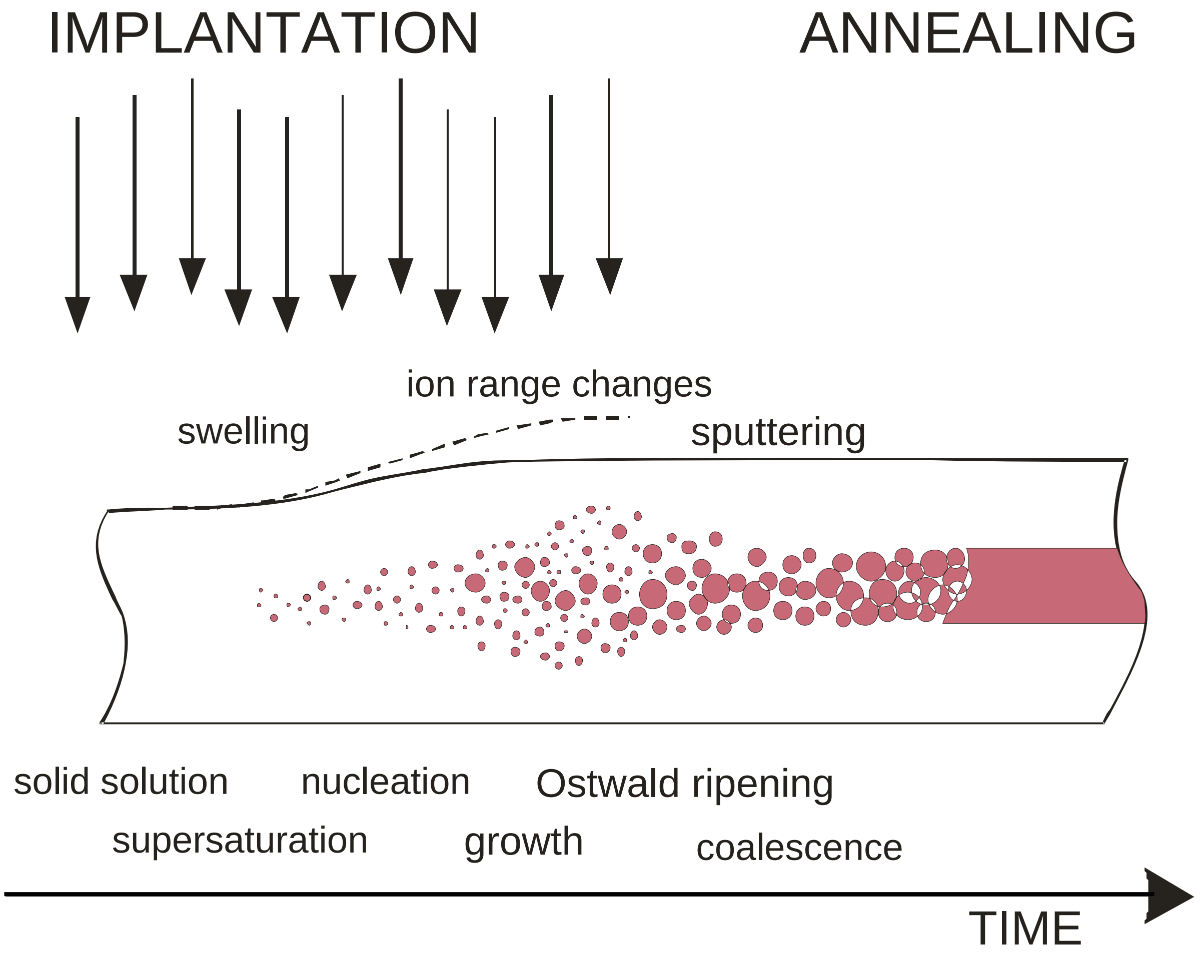


200 MeV ^{127}I, D = 3 x 10^{12} I/cm^2



C. D´Orleans et al., NIMB 225(2004)

ION BEAM SYNTHESIS



Ion Beam Synthesis of (Buried) SiC Layers

1. Implantation:

180 keV $C^+ \rightarrow$ Si(100)

T_i = 300, 450 °C

D = 8.5 x 10^{17} cm^{-2}

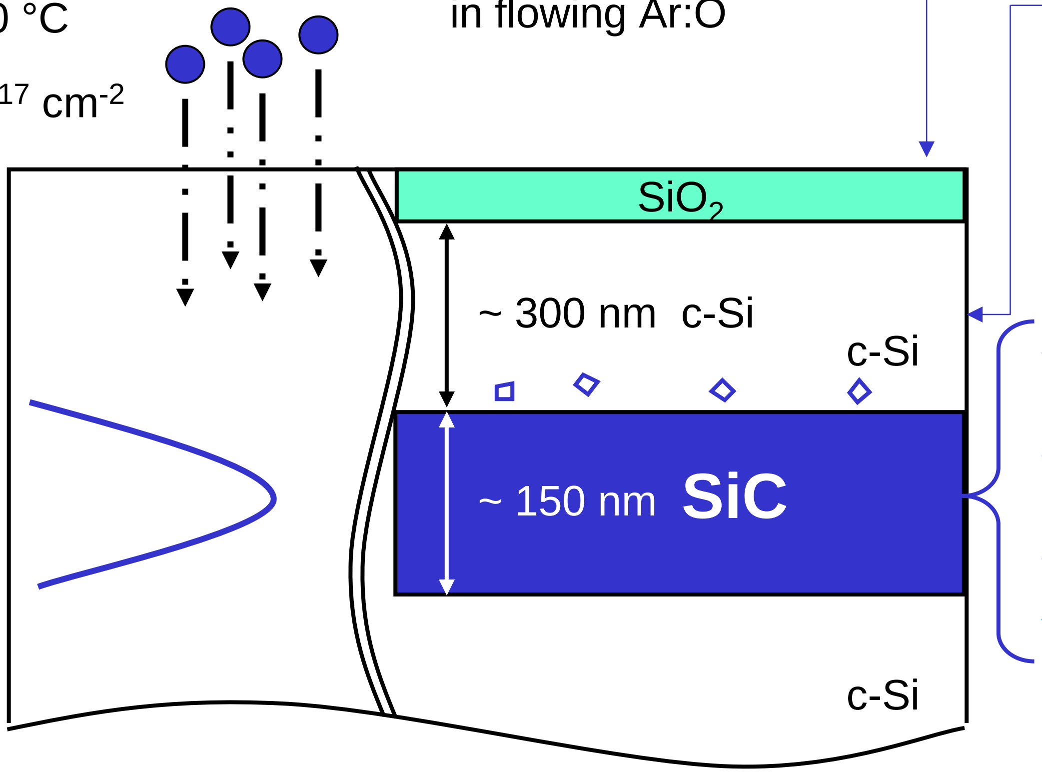
2. Furnace annealing:

10 h /1250°C

in flowing Ar:O

(3. SiO_2/Si top layer removal:)

HF or HF/HNO_3 dip



Selectable structure & composition:

- amorphous, carbon-rich a-SiC:C
- nanocrystalline nc-3C-SiC
- single-crystalline sc-3C-SiC

details in: NIM B 147 (1999) 249, NIM B 148 (1999) 528,
review in: Appl. Phys. A77 (2002) 27

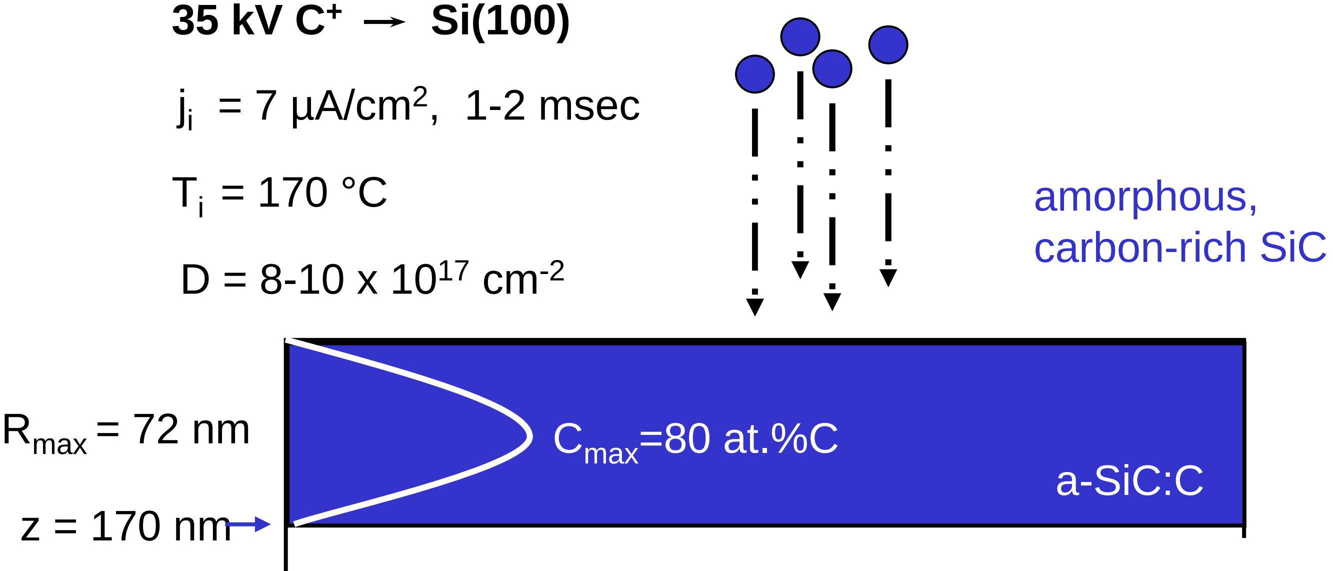
MEVVA Ion Beam Synthesis of a-SiC:C Layers

35 kV C^+ → Si(100)

$j_i = 7\ \mu A/cm^2$, 1-2 msec

$T_i = 170\ °C$

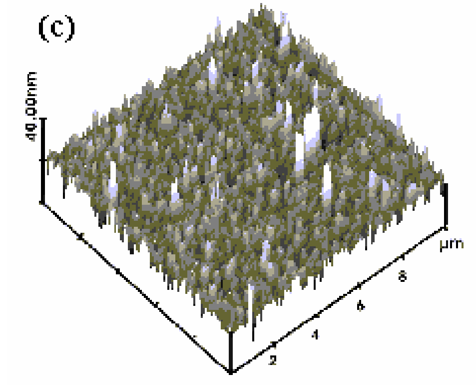
$D = 8\text{-}10 \times 10^{17}\ cm^{-2}$



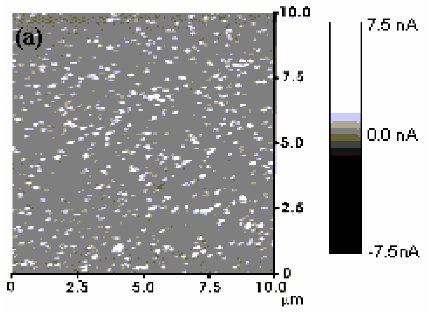
c-Si

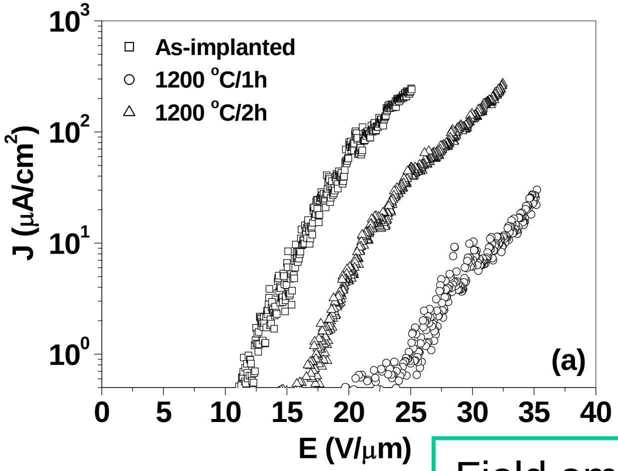
amorphous,
carbon-rich SiC

AFM



Conductive AFM

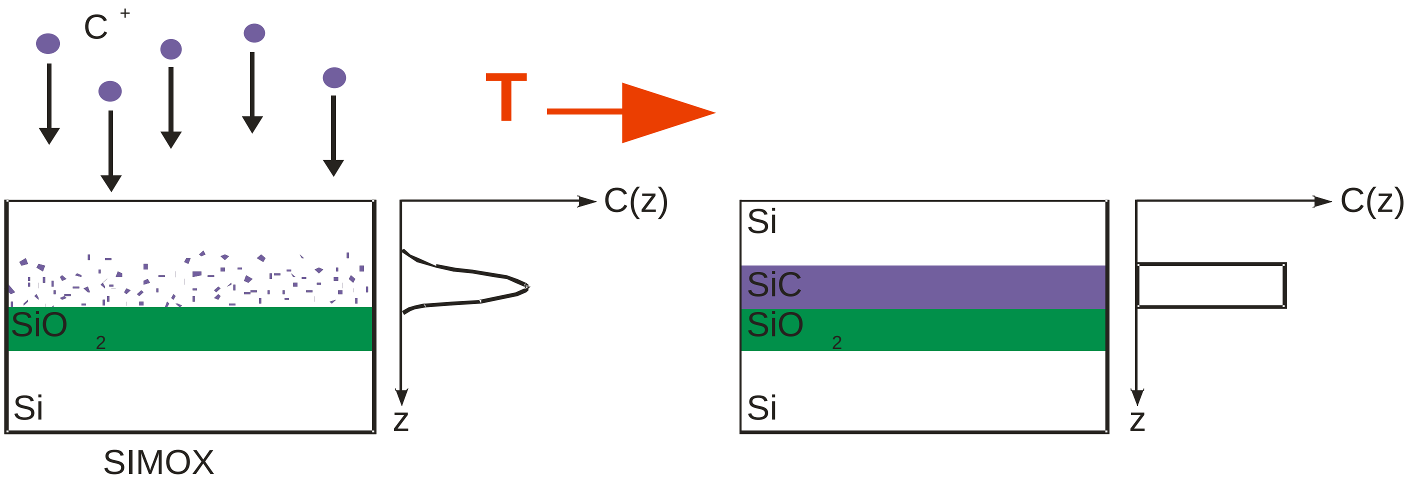


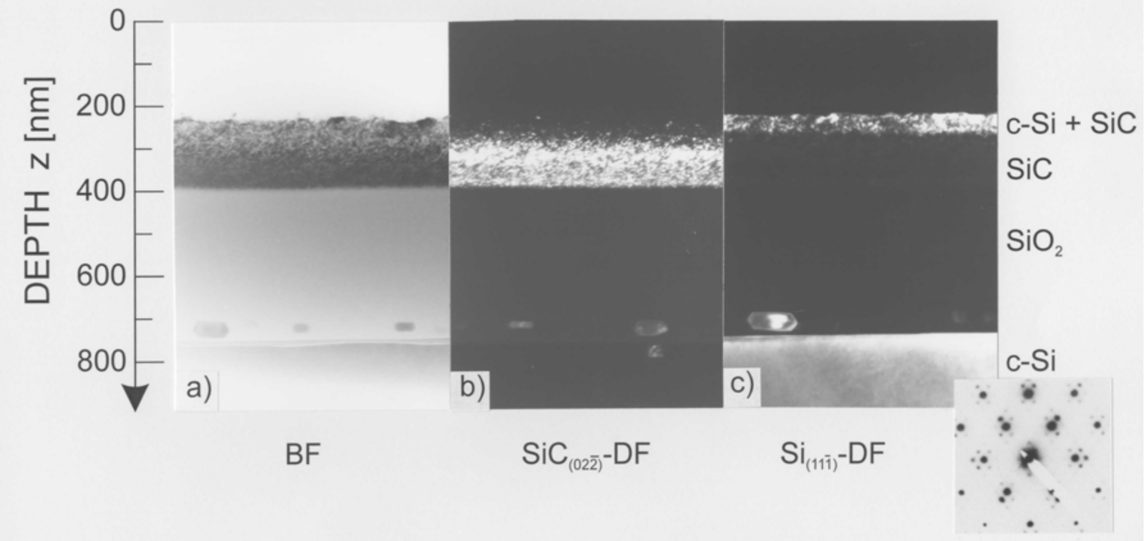


Field emission turn-on @1V/µm

morphology: APL 72 (1998) 1926
origin of field emission: APL 81(2002) 3942

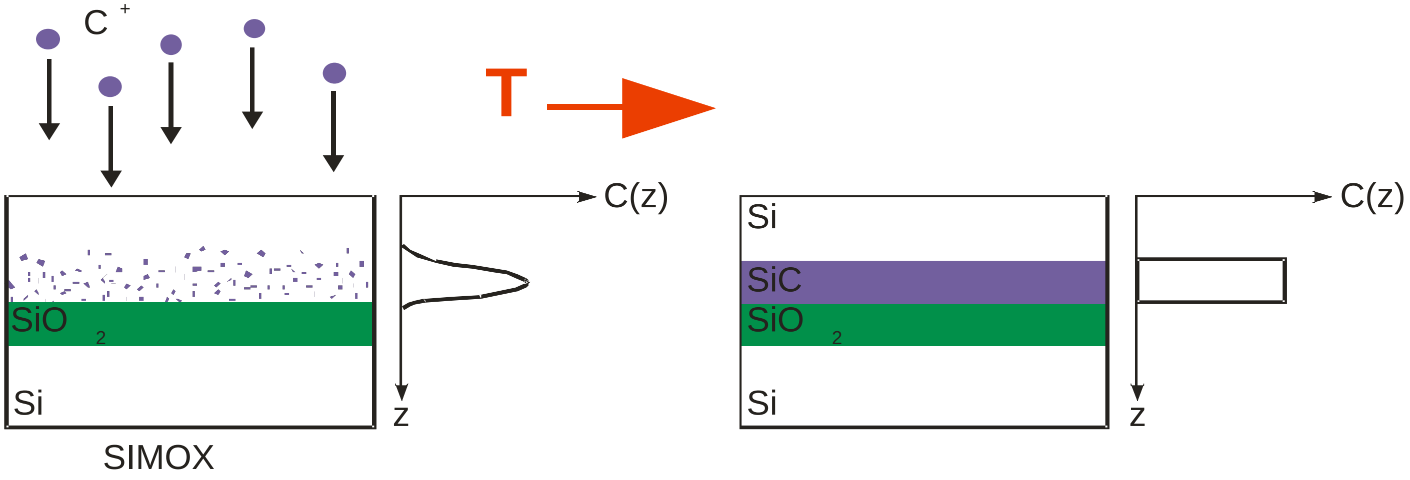
Ion Beam Synthesis of SiC Layers in SIMOX

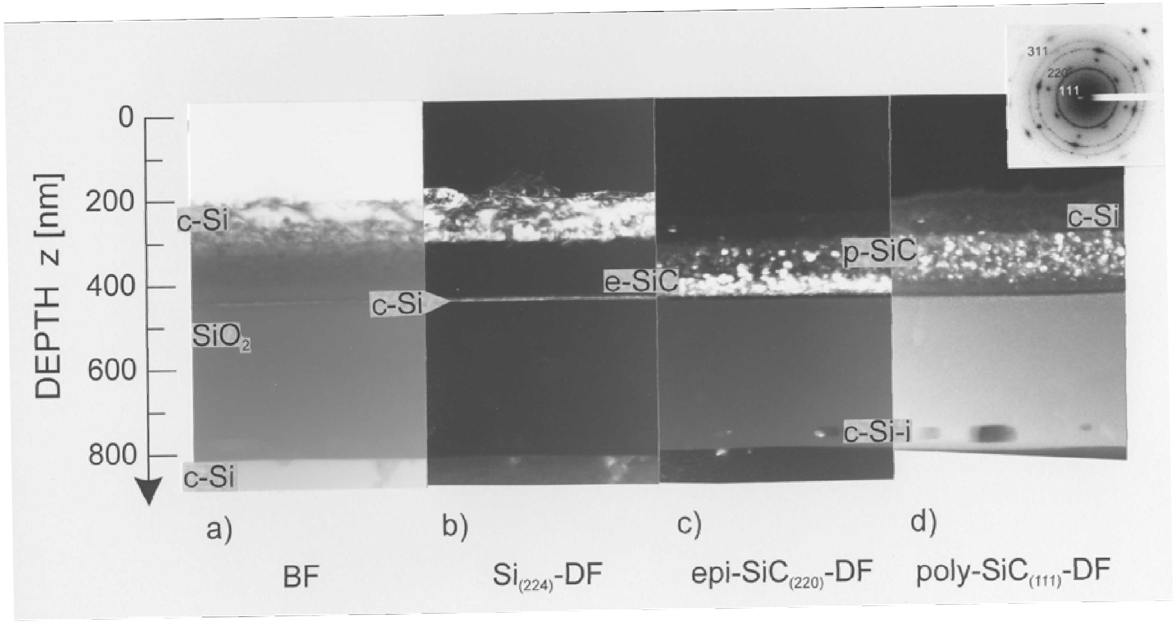




B. Götz, J.K.N. Lindner, B. Stritzker, Nucl. Instr. and Meth. B127/128 (1997) 333

Ion Beam Synthesis of SiC Layers in SIMOX

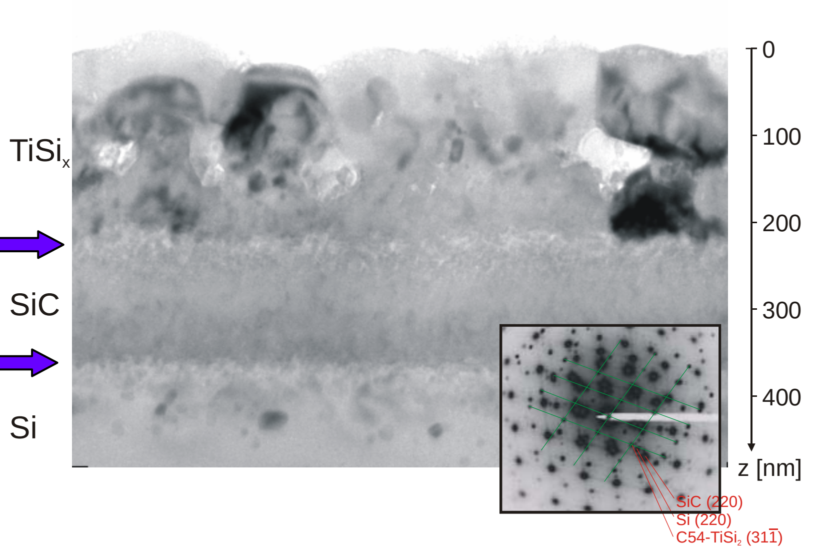




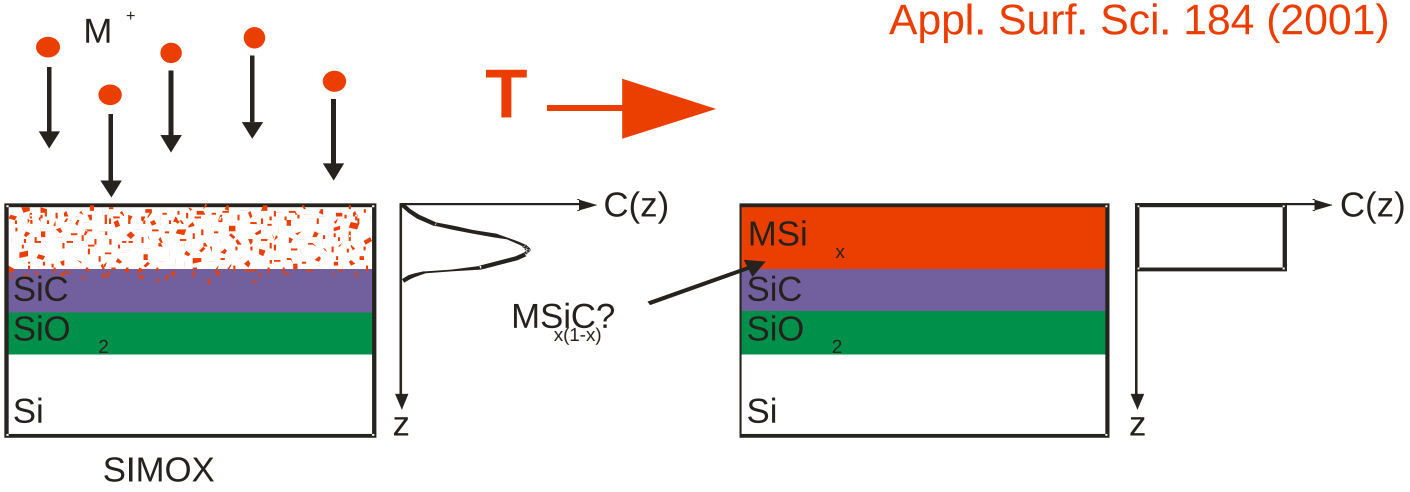
Ion Beam Synthesis of TiSi$_2$ Layers on SiC

direct contact

good interface



Appl. Surf. Sci. 184 (2001)



Summary

ION IMPLANTATION

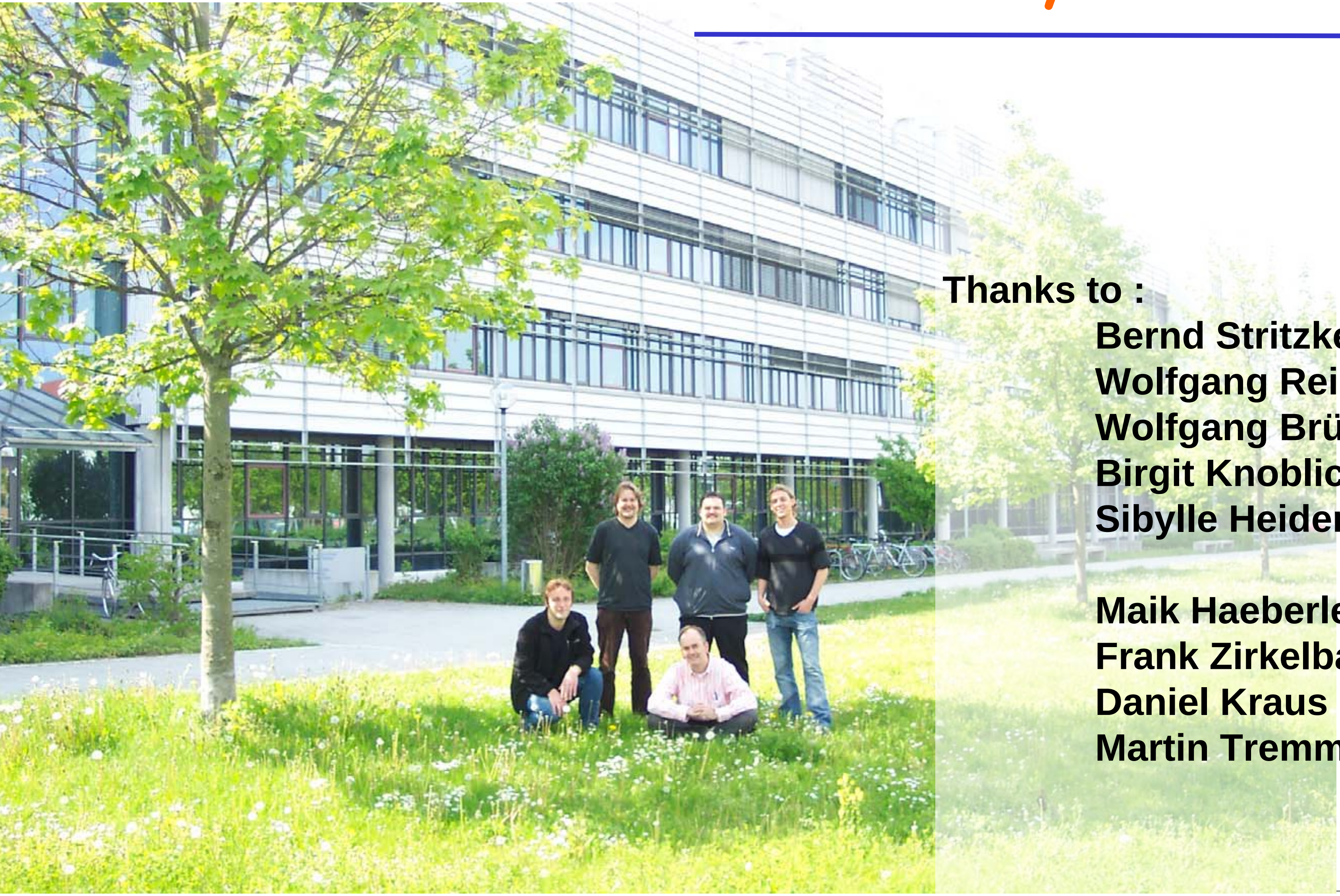
Today:

95 % of all doping steps done by implantation

The technique for the

- controlled insertion of atoms into a near surface layer
- nanoscale modification of structural properties

Thanks for your attention



Thanks to :

Bernd Stritzker
Wolfgang Reiber
Wolfgang Brückner
Birgit Knoblich
Sibylle Heidemeyer

Maik Haeberlen
Frank Zirkelbach
Daniel Kraus
Martin Tremmel

Recommended Reading:

- Ziegler, Biersack, Littmark; *The Stopping and Range of Ions in Matter*
- E. Rimini: *Ion Implantation: Basics to Device Fabrication*, (Kluwer)
- *Ion Implantation and Beam Processing*, ed.: J.S. Williams, J.M. Poate (Academic Press)
- M. Nastasi, J.W. Mayer, J.K. Hirvonen; *Ion - Solid Interactions: Fundamentals and Applications* (Cambridge University Press)
- Nuclear Instruments and Methods in Physics Research B