Applications of Ion Implanters

Jörg K.N. Lindner
ION IMPLANTATION

More than a standard technique for the doping of semiconductor devices

keV - MeV

... from \(^1\text{H}^+\) to \(^{238}\text{U}^{±n}\)

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 apparatuses
• 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
Wafer Handling System of an Implanter Endstation
Rotating Wafer Hub

beam

Plan view of a dedicated high-dose oxygen implanter

65 - 230 keV ≤ 100 mA O⁺ ~20 kW beam

72 kW lamp heater,
\[ T_i = 300 - 570°C, \]
\[ t_{\text{heat-up}} = 5 \text{ min.} \]
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 $S$:

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

Stopping power [eV/A]
Stopping of Ions in Matter: Energy Dependence

Stopping cross section $S$:

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

Stopping power ~ velocity: LSS region

Stopping power

nuclear
electronic

$N$: target density

Effective charge fluctuations: transition region

too fast to ionize: Bethe Bloch region

relativistic region

nuclear stopping dominates at low energies

electronic stopping dominates at high energies

$S_e + S_n$

$S_e$

$LSS$

$S_n$

$BB$

$E^{-1}$

$E^{1/2}$

$-\frac{1}{N} \frac{dE}{dx}$

$\left[ \text{MeV} \right] / \left[ \text{mg/cm}^2 \right]$

$\text{Energy} / \text{amu}$

Ziegler, Biersack, Littmark: universal potential
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 \( \Delta R_p \). 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 \( \beta \) values (800 keV - 60; 300 keV - 19; 100 keV - 7; 30 keV - 5).
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 $R_{\text{max}}$ 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
- Amorphous volumes
- Interstitial/substitutional impurities
- Coherent / incoherent precipitates

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Radiation damage and amorphization

Damage accumulation is a highly non-linear process!

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

Damage saturation by amorphization

2 MeV Si$^+$ → Si$_{1-x}$Ge$_x$

DOSE D [Si$^+$ cm$^{-2}$]

J.K.N.L., NIM B 127 (1997)
Ion-Solid-Interactions: Physics over Orders of Magnitude

Energy Deposition

Orders of Magnitude:
20 in time
13 in energy
10 in dose=concentr.

Times [sec]

Phase Transition

10^{-15} 10^{-12} 10^{-9} 10^{-6} 10^{-3} 10^0 10^3 10^6
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, BF₂ \( \{ \text{p-type doping} \) ...
- In \( \) ...
- P \( \) ...
- As \( \) ...
- Sb \( \) ...
- O \( \) ...
- (N) \( \) ...
- Si \( \) ...
- Ge \( \) ...
- C \( \) ...
- H \( \) ...
- He \( \) ...

Application of Ion Implantation in Semiconductor Industries and Research

Dose [ions/cm²]

Energy [MeV]

10^11

10^16

200 eV

3 MeV

Application of Ion Implantation in Semiconductor Industries and Research

![Graph showing various ion implantation applications](graph.png)
Ion beam synthesis of layers and nano-particles

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

Dose [ions/cm²]

- Single ion events

Energy [keV]

- R&D

- Dose [ions/cm²]

- Single ion events

Energy [MeV]
Lowest doses
Physical Limits to Silicon - CMOS Device Scale Down

Moore’s Law

(20 nm)^3: 4 \times 10^5 \text{ Si-atoms} + 80 \text{ P-atoms}

Degeneration

Attempts towards single ion implantations

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


Focused Ion Beam Etched Hole Pattern for SII masks

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

Energy requirements in future single ion implants

(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

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

Ion beam synthesis of layers and nano-particles

Energy [MeV]

Single ion events

Dose [ions/cm²]

Ion tracks

R&D
Tumor Therapy with Ions

Stopping cross section $\frac{dE}{dx} (\text{MeV/mg/cm}^2)$

Cell Survival Rate

Dose [Gy]

Depth [mm H$_2$O]

- LSS
- $S_e$
- $S_n$
- BB
- electronic

$\sim E^{1/2}$
$\sim E^{-1}$

source: GSI Darmstadt
Eye cancer treatment at Hahn-Meitner-Institute HMI Berlin with Protons

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

• Colloids
Self-Assembled Colloidal Crystal

Template for an photonic bandgap crystal

**MeV Ion Irradiation of Colloidal Particles and Crystals**

4 MeV Xe$^{4+}$, $D = 3 \times 10^{14}$ 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$^{4+}$, $D = 1 \times 10^{15}$ cm$^{-2}$, $T_i = 90$ K

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

75 keV C⁺ ions, \( D = 3.3 \times 10^{16} \text{ C/cm}^2 \), \( T_i = RT \)

X-section
EFTEM silicon map

100 nm
Application of Ion Implantation in Semiconductor Industries and Research

Ion beam synthesis of layers and nano-particles

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

Single ion events

Dose [ions/cm²]

Energy [MeV]

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Ion Tracks

E > 1 MeV/nucleon

TIME

10 nm

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Direct Evidence of Reduced Densities in Single Ion Tracks

350 MeV Au → NiO

EFTEM Thickness Map

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/cm². 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 $7 \times 10^7$ cm$^2$.

J. Chen et al., APL85 (2004)

Iron single crystals oriented along the [110] crystallographic axis

Vertical nanowire transistors

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.
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

Ion beam synthesis of layers and nano-particles

Single ion events

Dose [ions/cm²]

0.001 0.01 10 100

Energy [MeV]

10^18

10^16

10^14

10^12

10^10

R&D

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

Ion tracks

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Ion Beam Synthesis of Precipitate Layers and Homogeneous Layers

Ion-Implantation: Ion Profiles

Concentration

DOSE

DEPTH

Rp

R_max
ION BEAM SYNTHESIS

IMPLANTATION

ION RANGE CHANGES
swelling
sputtering

solid solution
nucleation
Ostwald ripening
supersaturation
growth
coalescence

ANNEALING

TIME
Optical Properties of Metallic Nanoclustes in Insulators

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

Classical Pottery from Deruta (Italy)

Formation by decomposition of metal salts

Formation of Metallic Nanoparticles in SiO$_2$

X-sectional TEM bright-field image

SiO$_2$

120 keV Ni$^+$
~ $10^{17}$ Ni/cm$^2$

100 nm
60 kV MEVVA Implantation Ni → Fused Silica Glass

D = $2 \times 10^{17}$ Ni/cm$^2$, $T_i = RT$

Nonlinear optical constant

$n = n_0 + \beta n_2$

In collaboration with PS Chung & SP Wong, CUHK

PS Chung, PhD thesis CUHK (2001)
Combinatorial Ion Beam Synthesis of Compound-Nanoclusters

Sequential implantation of keV Cd+ and Se+ ions into SiO₂

**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 \( d₀ \) of \( 2.85 \times 10^{16} \) cm².

I. Großhans et al., Proc. CAARI 2002
Adding complexity to Nanoparticles

190 keV Ne⁺, D = 1 x 10¹⁷ cm⁻², RT

Au-enriched “satellite” nanoparticles around original AuₓCu₁₋ₓ clusters

G. Mattei et al., PRL90 (2003)
Deformation of Metallic Nanoparticles in SiO₂

160 keV Co → SiO₂/Si, D = 1 x 10¹⁷ Co/cm²

200 MeV \(^{127}\text{I}\), D = 3 x 10¹² I/cm²

C. D’Orleans et al., NIMB 225(2004)
ION BEAM SYNTHESIS

IMPLANTATION

ANNEALING

TIME

ion range changes

swelling

sputtering

solid solution

nucleation

Ostwald ripening

supersaturation

growth

coalescence

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Ion Beam Synthesis of (Buried) SiC Layers

1. Implantation:
- 180 keV C⁺ Si(100)
- $T_i = 300, 450 \, ^\circ C$
- $D = 8.5 \times 10^{17} \, \text{cm}^{-2}$

2. Furnace annealing:
- 10 h /1250°C
- in flowing Ar:O

3. SiO₂/Si top layer removal:
- HF or HF/HNO₃ dip

Selectable structure & composition:
- amorphous, carbon-rich a-SiC:C
- nanocrystalline nc-3C-SiC
- single-crystalline sc-3C-SiC

**MEVVA Ion Beam Synthesis of a-SiC:C Layers**

35 kV C⁺ → Si(100)

\[ j_i = 7 \mu A/cm^2, \ 1-2 \text{msec} \]

\[ T_i = 170 \degree C \]

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

\[ R_{\text{max}} = 72 \text{ nm} \]

\[ C_{\text{max}} = 80 \text{ at.}\% \text{C} \]

\[ z = 170 \text{ nm} \]

**Conductive AFM**

**Field emission turn-on @1V/\mu m**

**morphology**: APL 72 (1998) 1926

**origin of field emission**: APL 81(2002) 3942
Ion Beam Synthesis of SiC Layers in SIMOX

Ion Beam Synthesis of SiC Layers in SIMOX
Ion Beam Synthesis of TiSi$_2$ Layers on SiC

Aim: Metallization of the SiC Layer

direct contact

good interface

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)


• Nuclear Instruments and Methods in Physics Research B