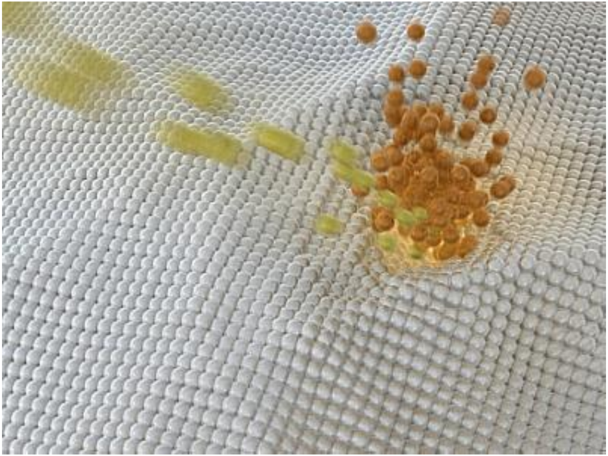
Physical techniques for nanofabrication

Ion implantation

Ion implantation

Atoms are introduced in the sub-surface zone of a solid substrate by accelerating ions with energy in the keV-MeV-GeV range.



Ion implantation

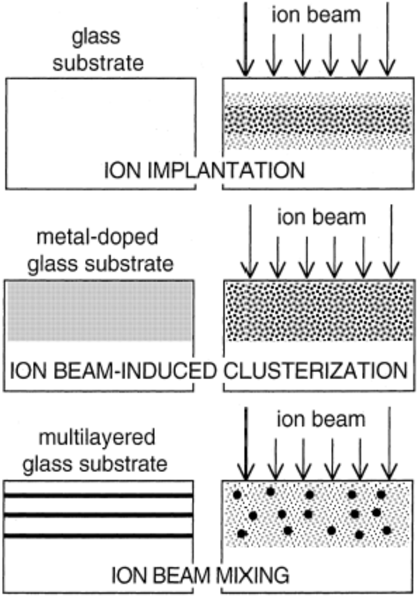
- Possibility to introduce virtually **any element** into the matrix (out of thermodynamic equilibrium)
- No **solubility limit** (supersaturation)
- Depth **concentration profile** control
- **Patterning** on prescribed geometries
- **Compatibility** with micro-electronic processes (low temperature)
- **Multiple** ion implantation (alloys or compounds)
- **Ion-beam processing**

Ion-beam processing

1. **Implantation** to form clusters of the implanted species

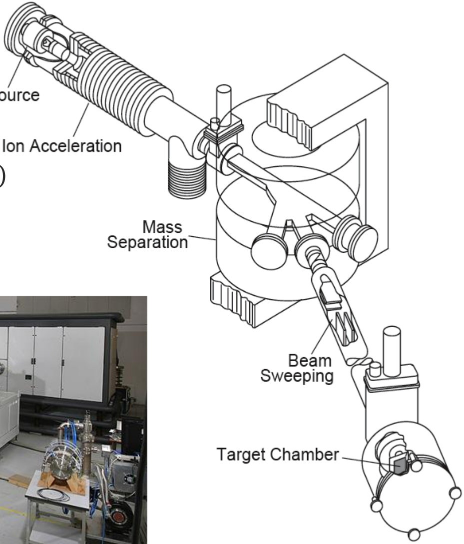
2. **Light-ions irradiation** (He, Ne, …) in glasses doped with the elements whose precipitation is to be promoted

3. **Heavy-ions irradiation** to induce **mixing** in multilayers



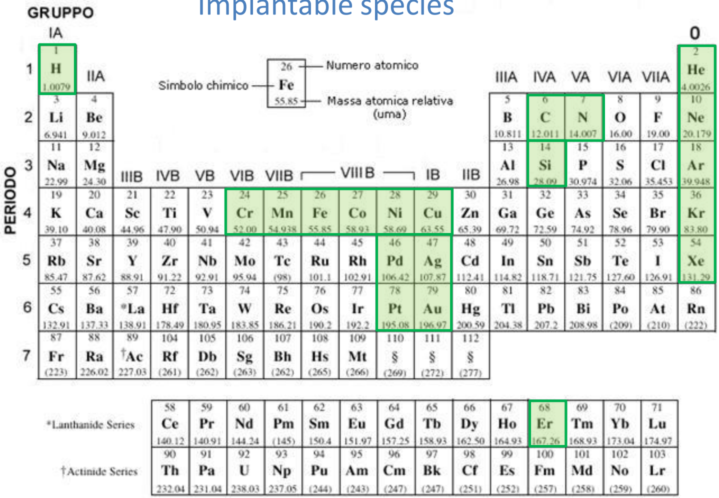
Ion implanter Danfysik 1090 (Legnaro, PD):

- $E_{ion} < 200\ keV$
- $J_{beam} < 2\ \mu A/cm^2$
- $Area_{raster} < 20 \times 20\ cm^2$
- $Fluence_{ion}$: $10^{11} \div 10^{17}\,cm^{-2}\ (\pm 10\%)$
- Double Faraday cage

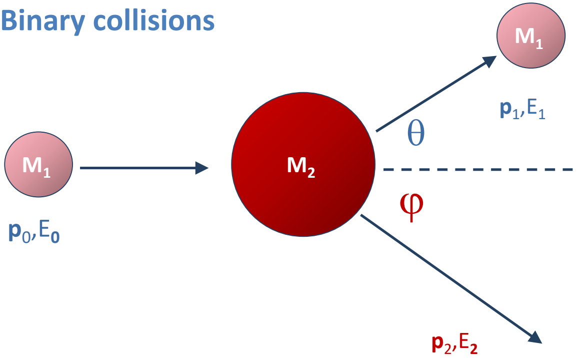


Ion implanter Danfysik 1090 (Legnaro, PD)

Implantable species



Binary collisions



$$V(r) = k\frac{Z_1 Z_2 e^2}{r}\chi(r)$$

Screening function

$$\chi(r) = \begin{cases} 0 & r \to \infty \\ 1 & r \to 0 \end{cases}$$

$$\chi_{TF}(r) = 1 - \frac{r}{\sqrt{3 + r^2}}$$

$$T_E = 4\frac{M_1 M_2}{(M_1 + M_2)^2} E_0 \sin^2\frac{\theta_c}{2} = \gamma E_0 \sin^2\frac{\theta_c}{2}$$

$$\theta_c = \theta + \sin^{-1}\left(\frac{M_1}{M_2}\sin\theta\right)$$

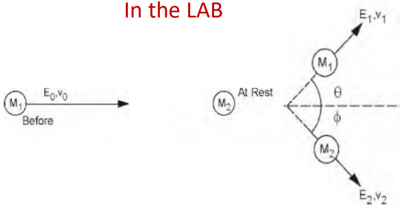
In the CM

T_E transferred energy

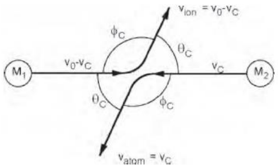
T_E is maximum when M_1=M_2

When $T_E > E_B$ (binding energy, 3-10 eV): atoms are removed from the target

In the LAB



In the CM



Ex.: 100 keV B on Si at θ = 45° (in the Lab)

$$M_1^B = 10$$
$$M_1^{Si} = 28$$

$$\theta_c = \theta + \sin^{-1}\left(\frac{M_1}{M_2}\ \sin\theta\right) = 59.6° \quad \text{CM}$$

$$T_E = 4\frac{M_1 M_2}{(M_1+M_2)^2} E_0 \sin^2\frac{\theta_c}{2} = \gamma E_0 \sin^2\frac{\theta_c}{2}$$

$$\gamma = 0.78$$

$$\sin^2\frac{\theta_c}{2} = 0.247$$

$$\gamma \sin^2\frac{\theta_c}{2} = 0.192$$

$$T_E = 19.2\ keV$$

Energy Loss

When an energetic ions enters a solid target it undergoes collisions loosing its initial energy at a typiucal rate of dE/dx ~ 0.1-1 keV/nm

Energy Loss

$$\frac{dE}{dx} = \left.\frac{dE}{dx}\right|_n + \left.\frac{dE}{dx}\right|_e$$

Coulomb interaction with the screened nuclear charge (elastic energy loss)

Interaction with the electronic cloud (inelastic energy loss)

Stopping cross-section S

Stopping

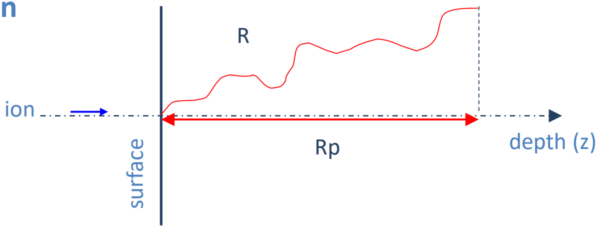
Energy loss per diffusion center $S \equiv \frac{1}{N}\frac{dE}{dx} = S_n + S_e$

N: densità atomica target (atomi/nm^3)

S_n(E): stopping nucleare

S_e(E): stopping elettronico

Concentration



Ion Range

$$R \equiv \int_{E_0}^{0} \left(\frac{dE}{dx}\right)^{-1} dE = \frac{1}{N} \int_{E_0}^{0} \frac{dE}{S(E)}$$

Projected Range Rp:

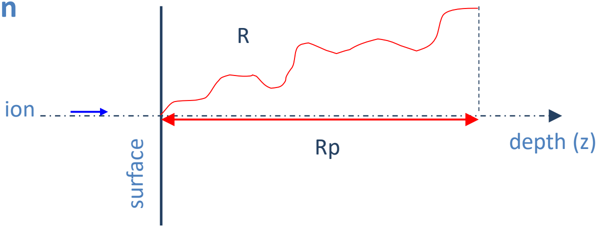
$$R_P = \frac{1}{N_{ion}} \sum_{j}^{N_{ion}} z_j \cong \frac{R}{1 + \frac{M_2}{3M_1}}$$

Straggling ΔRp: HWHM = semilarghezza picco di conc.

$$\Delta R_P = \sqrt{\frac{1}{N_{ion}} \sum_{j=1}^{N_{ion}} \left(z_j - R_P\right)^2}$$

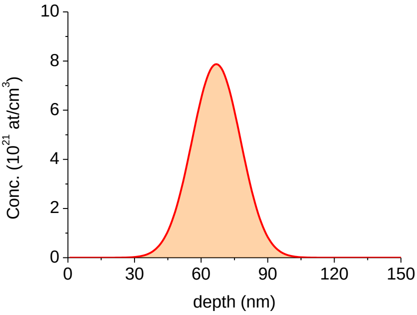
(average over N_{ion} ions)

Concentration



Concentration profile (~ gaussian)

$$C(z) = A \exp\left[-\frac{1}{2}\left(\frac{z - R_P}{\Delta R_P}\right)^2\right]$$



Dose or Fluence (atomi/cm²)

$$D = \int_0^\infty C(z)\ dz$$

Ion implantation

Example: He in SiO_2

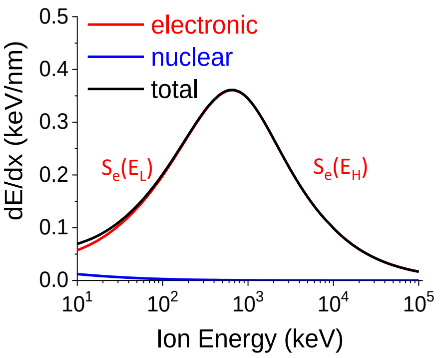
Ion: He [2] , Mass = 4.003 amu

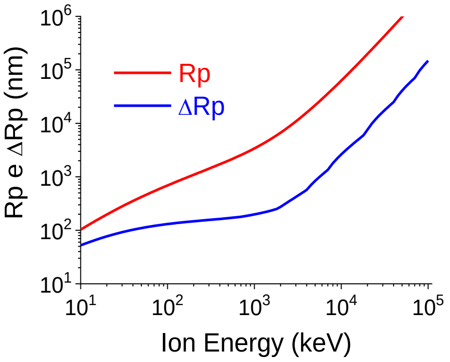
Target: SiO_2

Target Density = 2.32 g/cm^3 = 6.976 x 10^{22} atoms/cm^3

Target Composition

Atom Name	Atom Numb	Atomic Percent	Mass Percent
O	8	66.67	53.26
Si	14	33.33	46.74





J. P. Biersack and L. Haggmark, Nucl. Instr. and Meth., vol. 174, 257, 1980
SRIM code: http://www.srim.org/

Ion implantation

Example: Au in SiO_2

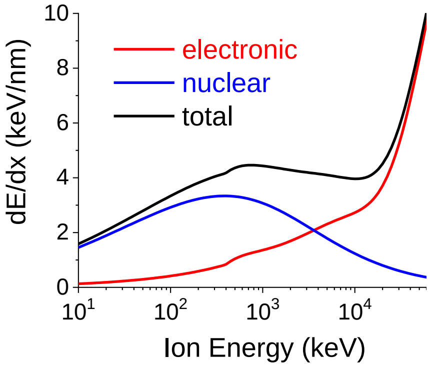
Ion: Au [79] , Mass = 196.967 amu

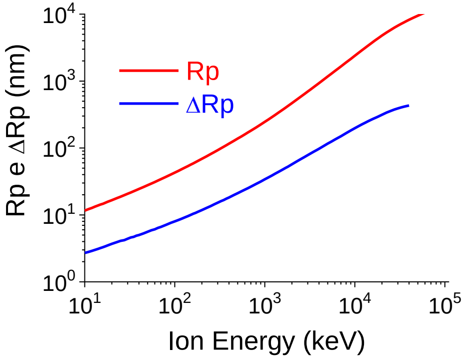
Target: SiO_2

Target Density = 2.32 g/cm^3 = 6.976 x 10^{22} atoms/cm^3

Target Composition

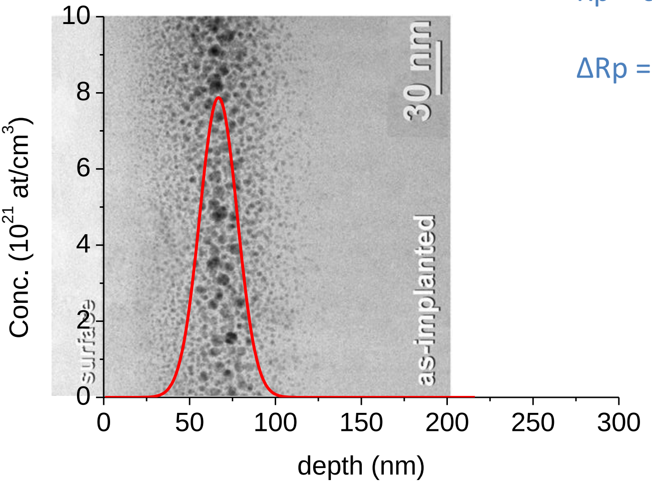
Atom Name	*Atom Numb*	*Atomic Percent*	*Mass Percent*
O	8	66.67	53.26
Si	14	33.33	46.74





J. P. Biersack and L. Haggmark, Nucl. Instr. and Meth., vol. 174, 257, 1980
SRIM code: http://www.srim.org/

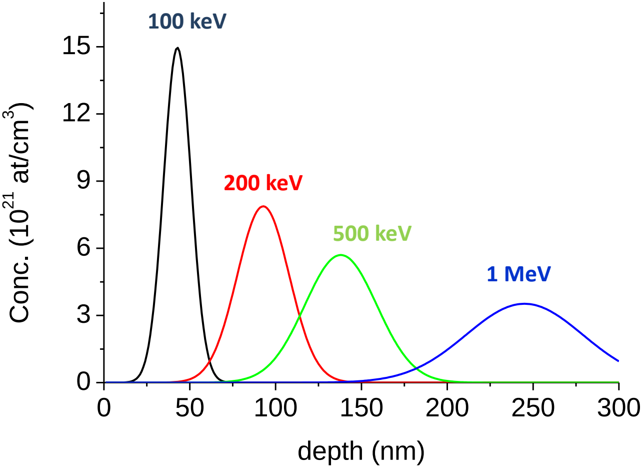
Example: Au 190 keV, 3×10^{16} ion/cm^2 in SiO_2



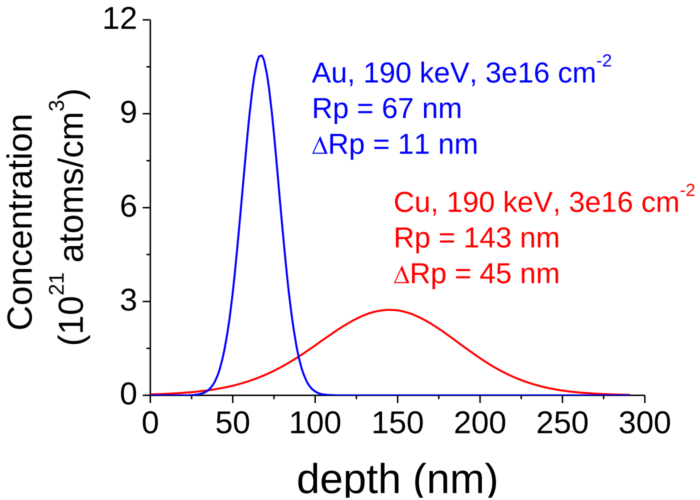
Rp = 67 nm

ΔRp = 11 nm

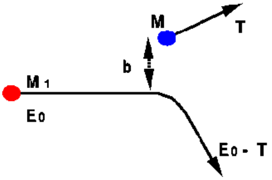
Example: Au in SiO_2 – dose $3{\times}10^{16}$ at/cm^2



Example: Au o Cu in SiO_2



Some definitions for Defect Configurations



- ***Displacement*** = The process where an energetic incident atom knocks a lattice atom off its site.

- ***Vacancy*** = A lattice site without an atoms. Originally all lattice sites are occupied, and displacements cause vacancies.

- ***Interstitial Atoms*** = Atoms which were knocked out of their original site, and come to a stop in the solid. Also the incident ions, when they stop, are considered interstitial atoms.

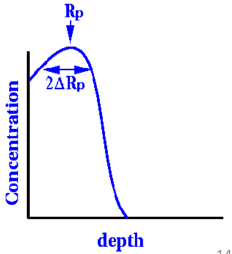
- ***Replacement Collisions*** = Atom sites with new atoms, identical to their original atom. This is the only mechanism in which a vacancy may be re-occupied.

Some definitions for Energies

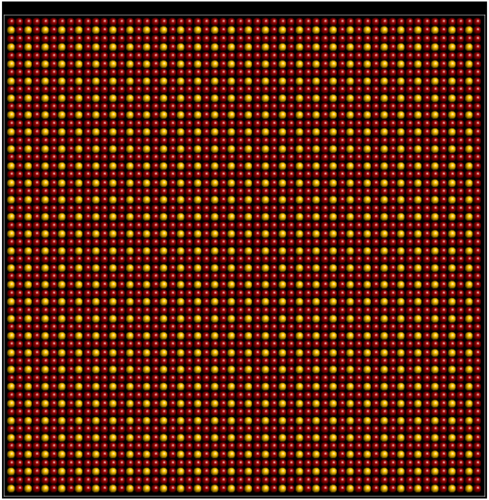
- ***E_d = Displacement Energy***, the minimum energy required to knock a target atom far enough away from its lattice site so that it will not immediately return. This minimum energy produces a "*Frenkel Pair*" = a single vacancy and a nearby interstitial atom, which is the most fundamental type of damage caused by an ion. (~ **20-50 eV**)

- ***E_b = Lattice Binding Energy***, the minimum energy needed to remove an atom from a lattice site (proportional to the sublimation enthalpy ΔH_s). It takes energy to break electronic bonds and displace an atom from a lattice site. The lattice binding energy must be smaller than the Displacement Energy ($E_b < E_d$) (**3-10 eV**)

- ***E_s = Surface Binding Energy.*** the energy required to remove a surface atom from its lattice site is less than if it was inside the solid and surrounded by other atoms. A surface atom has fewer electronic bonds which must to broken. Very important for sputtering (removal of surface atoms).

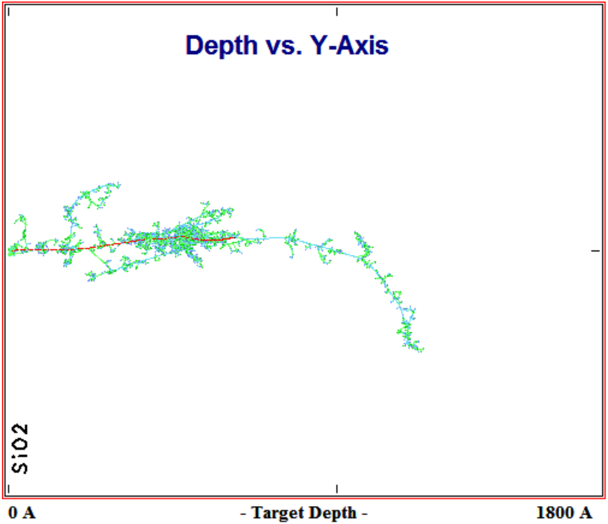


Disordering by a 10 keV Au -> Cu_3Au cascade



K. Nordlund, Univ. Helsinki, http://beam.acclab.helsinki.fi/~knordlun/

Collisional Cascade

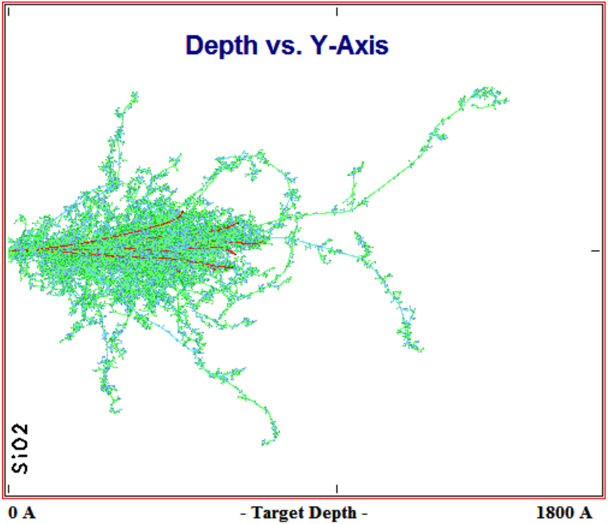


Au 190 keV in SiO_2

1 Au ion

SRIM code: http://www.srim.org/

Collisional Cascade



Au 190 keV in SiO_2

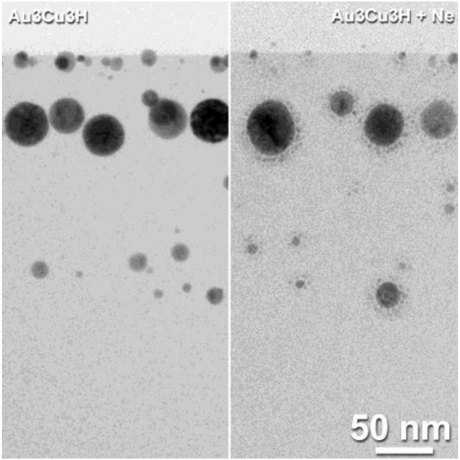
10 Au ions

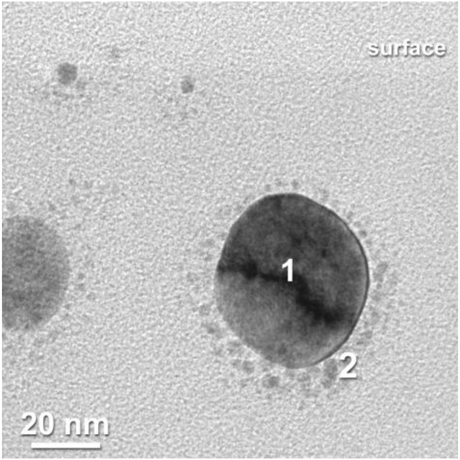
SRIM code: http://www.srim.org/

Ion Beam Processing

$Au_xCu_{(1-x)}$ alloy NCs in SiO_2

Ne^+ irradiation





100 keV
5.2 x 10^{16} Ne^+/cm^2

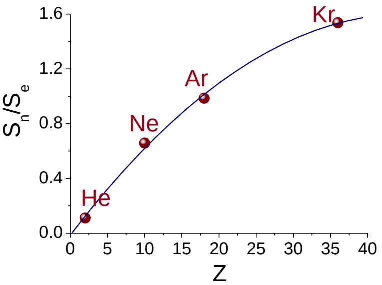
G. Mattei *et al.*, Phys. Rev. Lett. 90 (2003) 085502

Ion	Energy (keV)	Fluence (ions/cm^2)	Current dens. (μA/cm^2)	$S_n = E_{nucl}/E_{tot}$ (%)	$S_e = E_{el}/E_{tot}$ (%)
He^+	25	$32 \cdot 10^{16}$	6.3	10	90
Ne^+	100	$5.2 \cdot 10^{16}$	1.6	43	57
Ar^+	190	$2.5 \cdot 10^{16}$	0.8	50	50
Kr^{2+}	380	$1.2 \cdot 10^{16}$	0.4	67	33

Energy → Range ~ 3 $R_p^{(Au,Ag)}$
(~ 210 nm)

Fluence → Constant energy density
(~ 180 keV/nm^3)

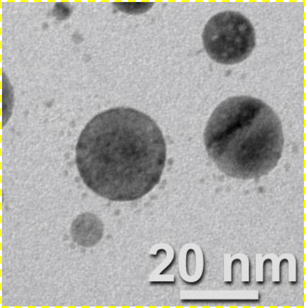
Current density → Constant power density
(~ 2.5x10^{-8} W/cm^2)



G. Mattei *et al.*, Phys. Rev. Lett. 90 (2003) 085502

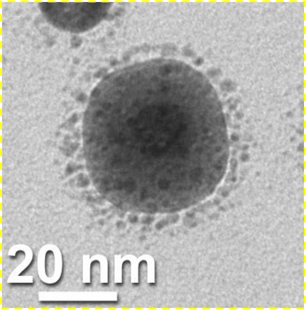
Ion Beam Processing

He^+



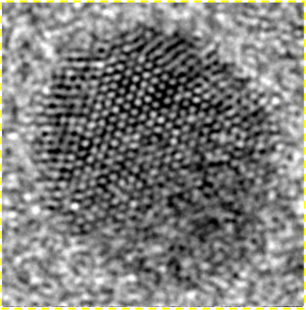
25 keV
32×10^{16} He^+/cm^2
J = 6.3 μA/cm²

Ne^+



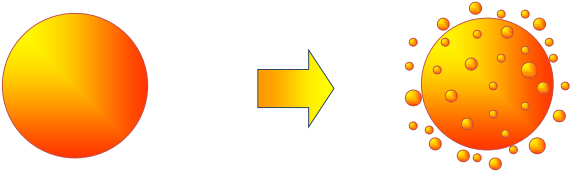
100 keV
5.2×10^{16} Ne^+/cm^2
J = 1.6 μA/cm²

Kr^{++}



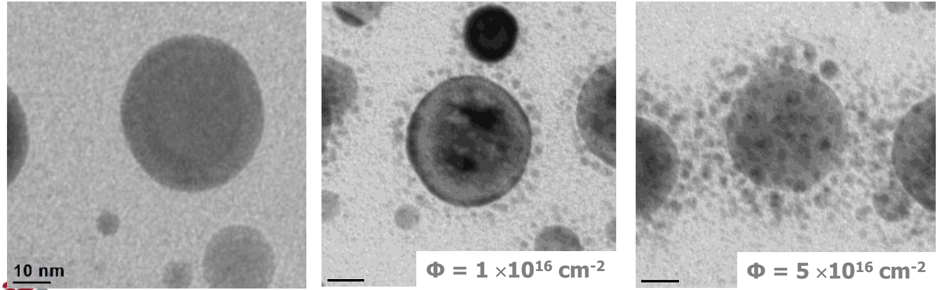
380 keV
1.2×10^{16} Kr^{++}/cm^2
J = 0.4 μA/cm²

Ion irradiation

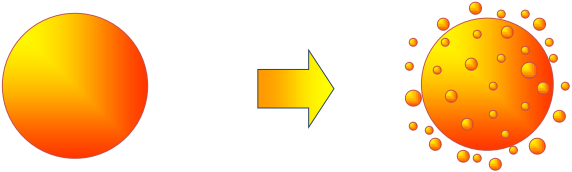


Core + Satellites
=
NanoPlanets

Ar$^+$ 190 keV

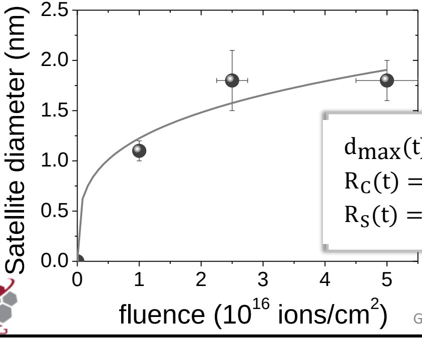


Ion irradiation

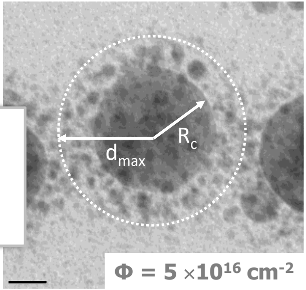


Core + Satellites
=
NanoPlanets

Ar$^+$ 190 keV

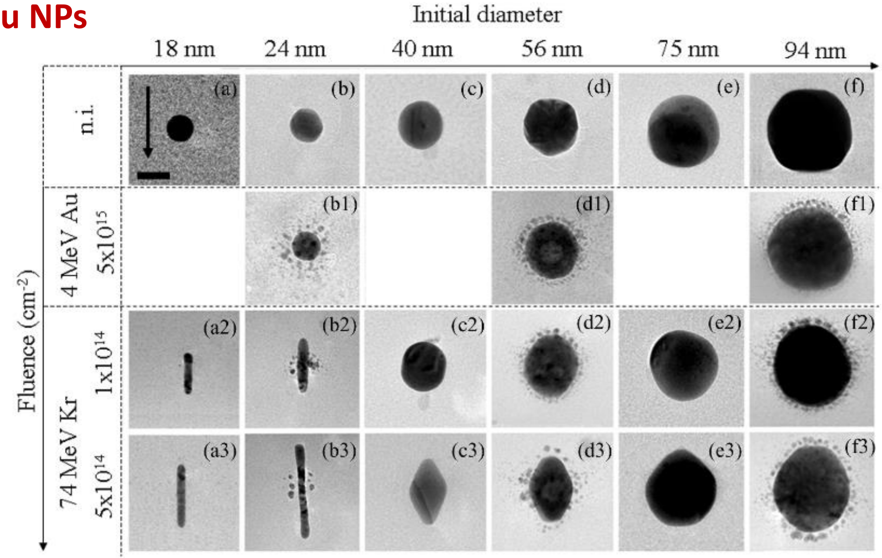


$$d_{max}(t) = C_1 t^{1/2}$$
$$R_C(t) = R_C(0) - C_2 t^{1/3}$$
$$R_S(t) = C_3 t^{1/3}$$



G. Mattei *et al.* Nucl. Instrum Meth. B **240** 128 (2005)

Au NPs


Initial diameter
18 nm
24 nm
40 nm
56 nm
75 nm
94 nm
n.i.
4 MeV Au
5x10^15
74 MeV Kr
1x10^14
5x10^14
Fluence (cm^-2)
(a)
(b)
(c)
(d)
(e)
(f)
(b1)
(d1)
(f1)
(a2)
(b2)
(c2)
(d2)
(e2)
(f2)
(a3)
(b3)
(c3)
(d3)
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