Ioni energetici nella sintesi e caratterizzazione di materiali e dispositivi avanzati

Valentino Rigato

LNL - 18 novembre 2021 - PID

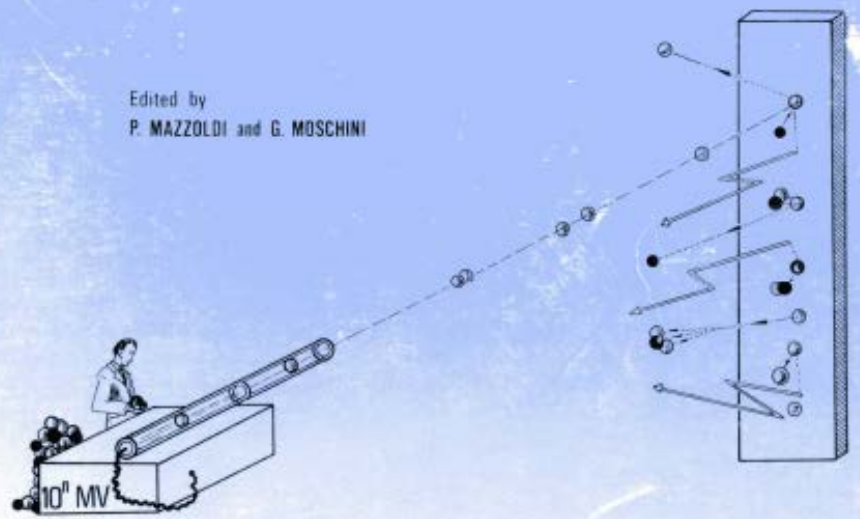
Proceedings

International Simposium

on

THREE-DAY IN DEPTH-REVIEW ON THE NUCLEAR ACCELERATOR IMPACT IN THE INTERDISCIPLINARY FIELD

Edited by
P. MAZZOLDI and G. MOSCHINI



Laboratori Nazionali di Legnaro (Padova), Italy

May 30th – June 1st, 1984

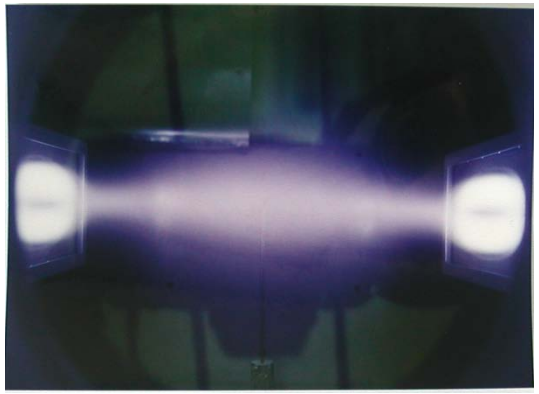
ENERGIA E CAMPI DI APPLICAZIONE DI FASCI IONICI

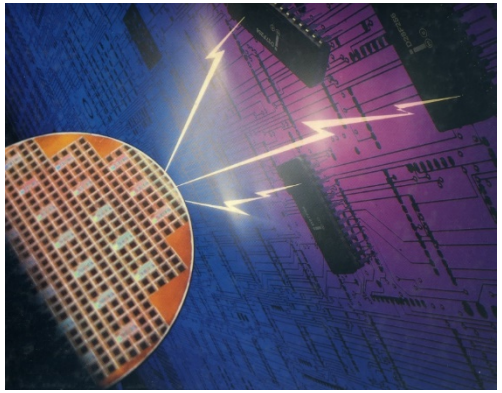
IONI PESANTI
Ar, Xe, Kr, Metalli

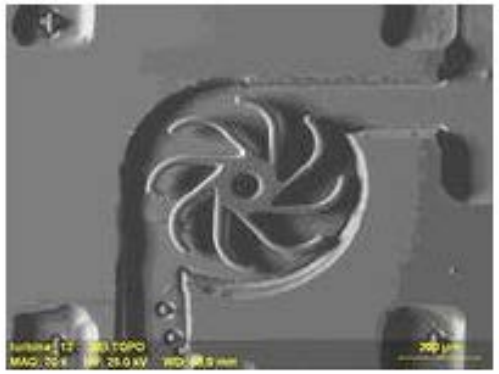
IONI PESANTI
C, N - B, P, As….

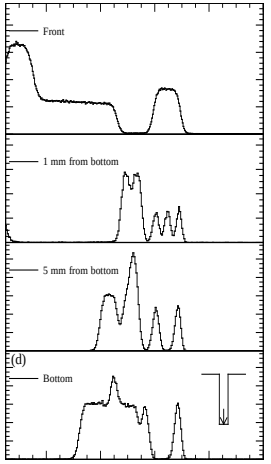
IONI LEGGERI
Protoni, He, Li

1eV 1000eV 1keV 500keV 1MeV 10MeV







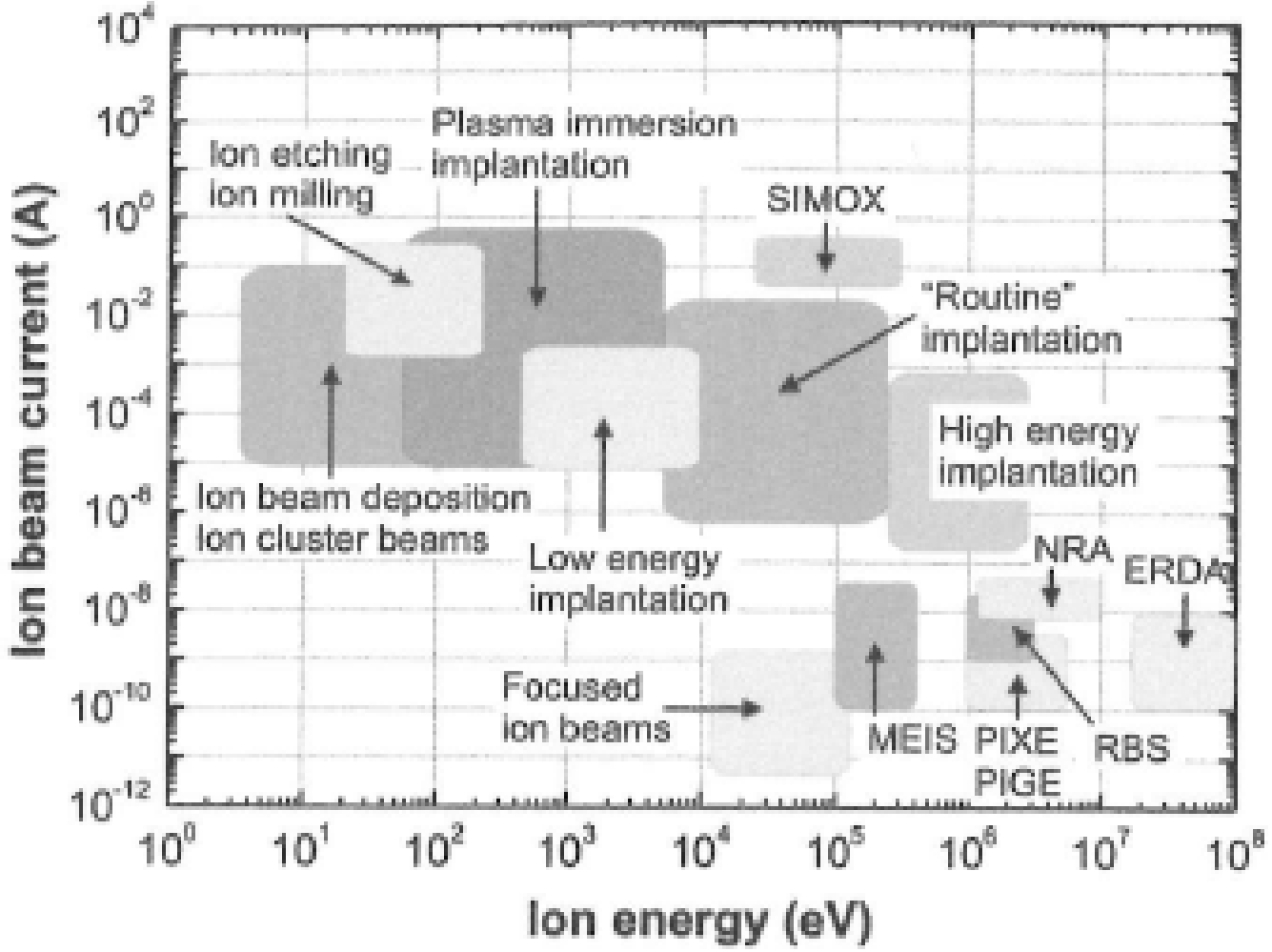


Sintesi di nuovi materiali
Trattamenti superficiali
Plasmi a bassa pressione

Impiantazione ionica
Drogaggio di semiconduttori

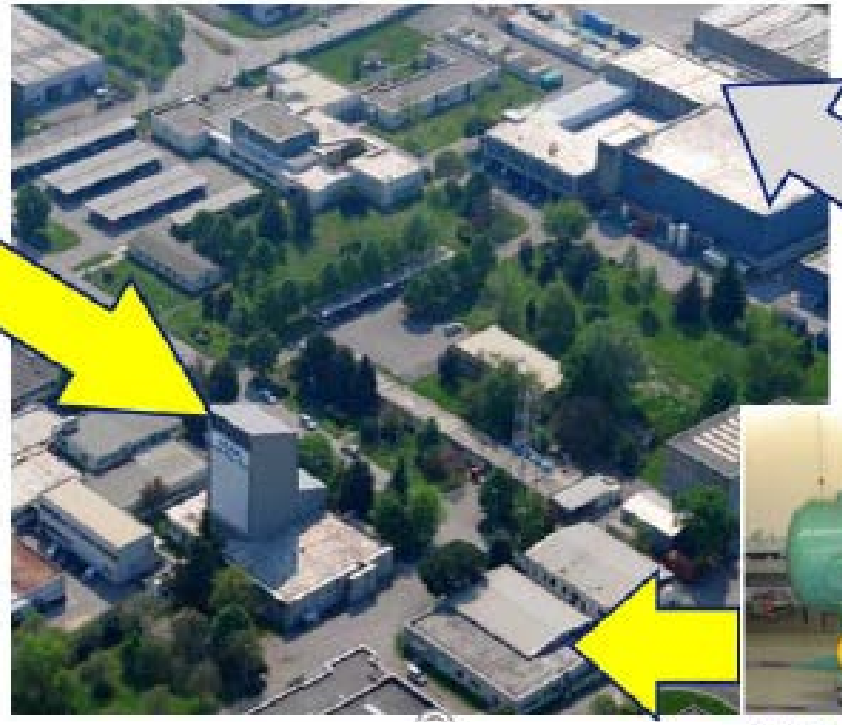
Microanalisi di materiali (RBS, PIXE, PIGE, ERD, NRA)
Microfabbricazione

Ion current – energy map of ion beam techniques for material processing and analysis



Acceleratori usati in esperimenti di fisica interdisciplinare presso i Laboratori Nazionali di Legnaro

CN: 1-6 MV
(Van de Graaff)



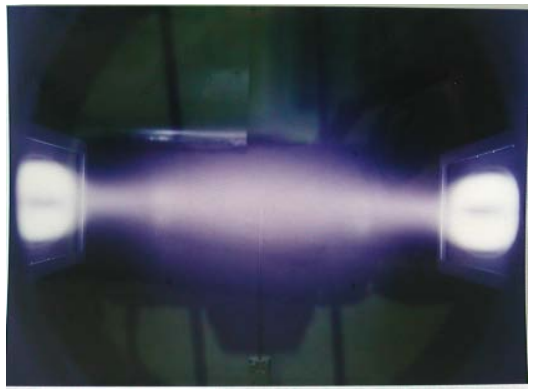
TANDEM-
XTU- ALPI

AN2000: 0.2-2.2MV
(Van de Graaff)

200keV-6MeV

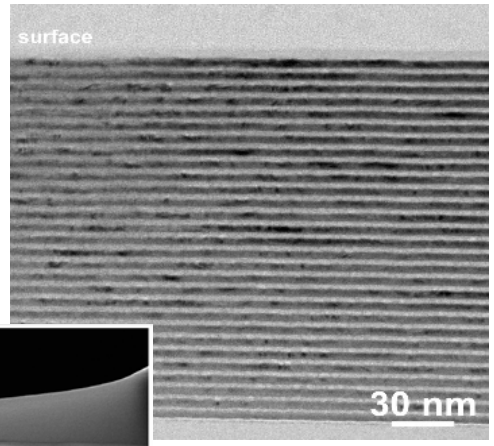
LABORATORIO DI SINTESI E CARATTERIZZAZIONE DI MATERIALI AVANZATI

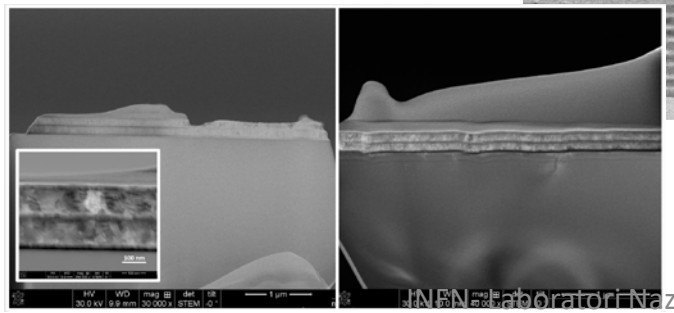
Synthesis and Process Development



- Plasma Sputtering Deposition
- Plasma Diagnostics
- Ion-solid interaction

- Low Friction, High Hardness Nanoscaled Materials and Multilayers
- Insulating Oxides
- High Performance Plastics

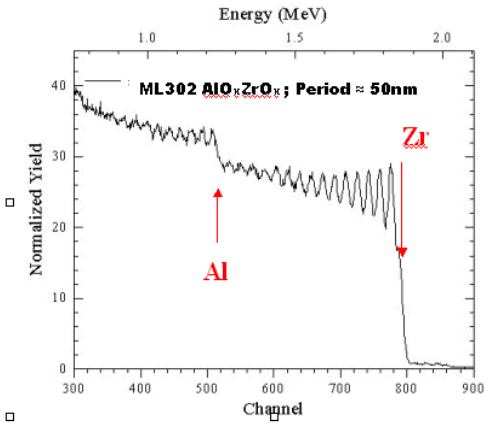


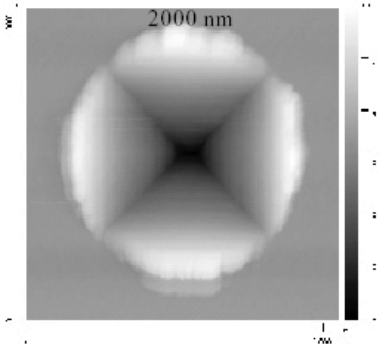


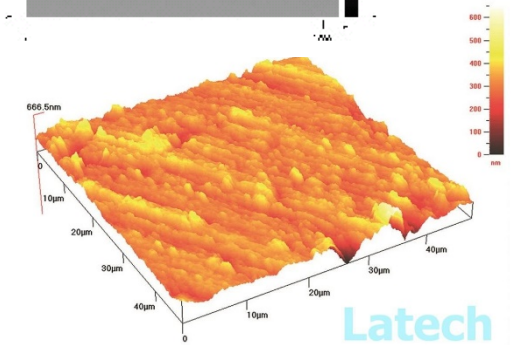
Characterization of Physical Properties

Composition

- Ion Beam Analysis (RBS, NRA, ERDA, PIXE)
- Microbeam (Micro-PIXE 2-D trace element analysis)





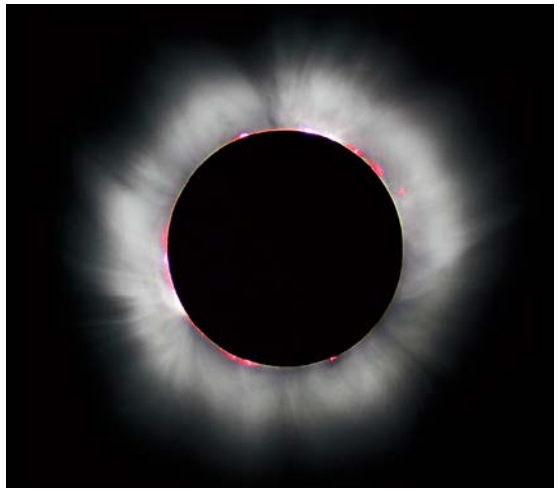


Morphology, Mechanical prop.

- Nano Hardness, Elastic modulus
- Adhesion (Micro-Scratch)
- Intrisic Stress
- Atomic Force Microscopy & SEM

IL **PLASMA** COME SORGENTE DI IONI

PLASMI (ESEMPI)



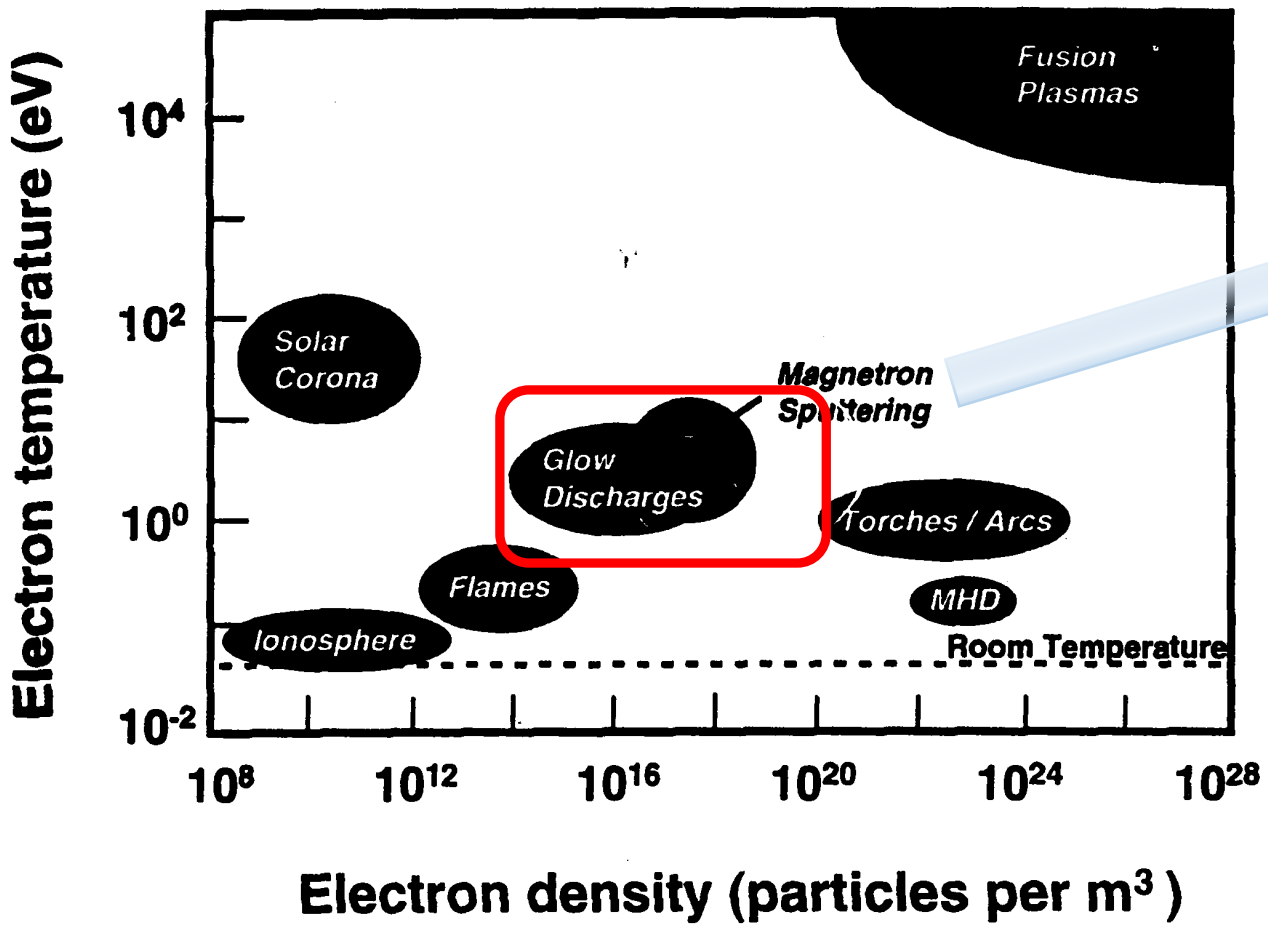
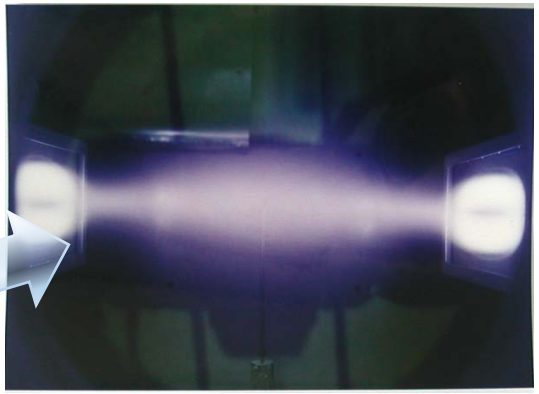


Figure 1. Classification of plasmas as a function of electron temperature and density. A convenient unit of temperature is the electron volt (eV) where 1 eV equals 11,600 K through the Boltzmann constant.



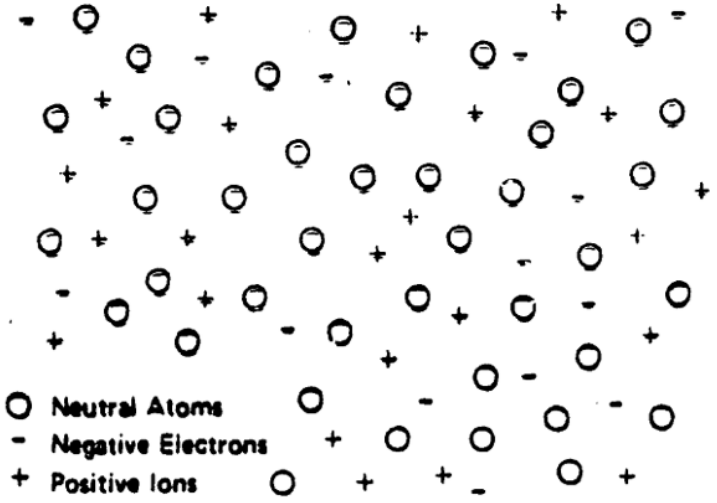
PLASMA = GLOW DISCHARGE = IONIZED GAS
PLASMA IS OUR EXTENDED SOURCE OF IONS

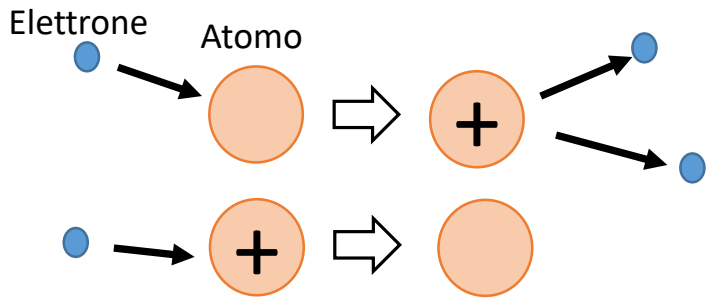
LOW PRESSURE PLASMA: a plasma derived by a low pressure gas
Typical gas pressures for plasma sputtering: 10^{-4} to 10^{-1} mBar

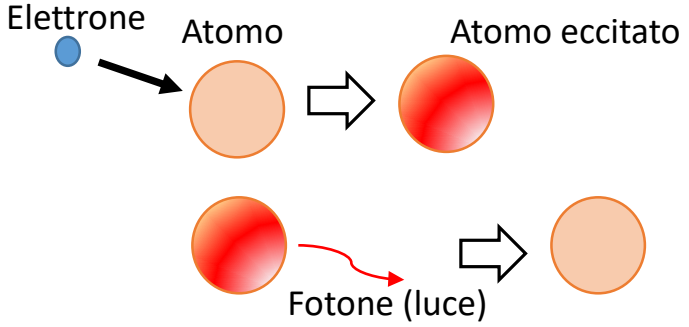
Simple picture:

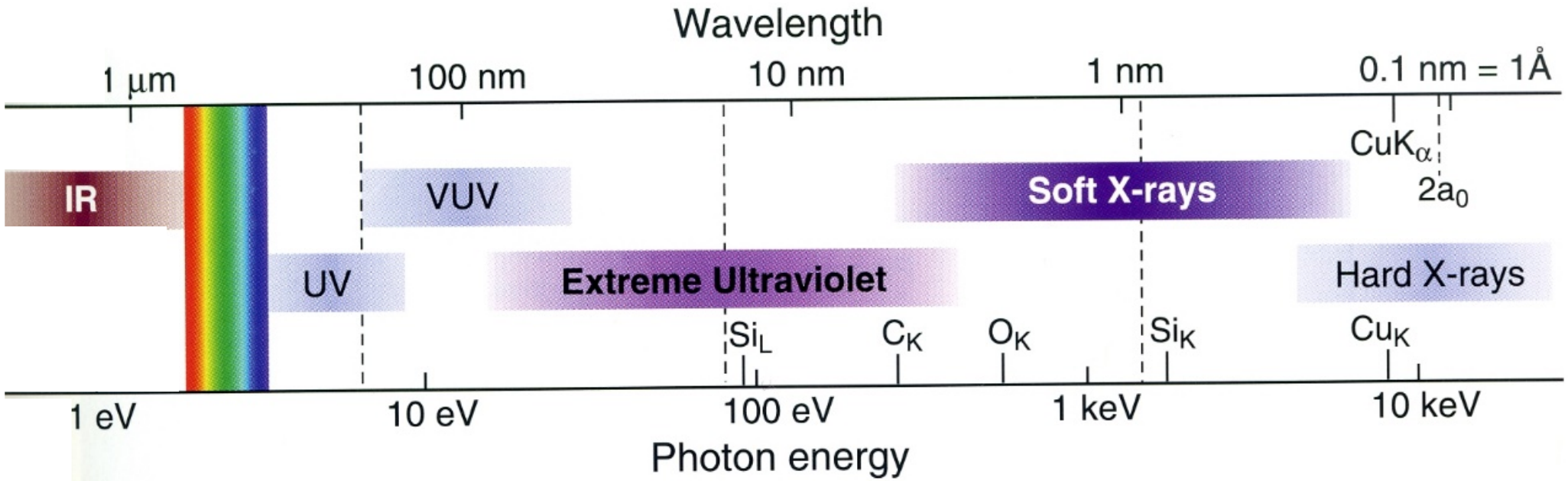
- Electron gas in thermal equilibrium
- Ion Gas in thermal equilibrium
- Neutral gas (obviously) in thermal equilibrium

MAIN Phenomena:
IONIZATION + RECOMBINATION
EXCITATION (Dissociation)+ DE-EXCITATION (Light emission)








Wavelength
1 μm
100 nm
10 nm
1 nm
0.1 nm = 1Å
IR
VUV
UV
Extreme Ultraviolet
Soft X-rays
Hard X-rays
CuKα
2a0
SiL
CK
OK
SiK
CuK
1 eV
10 eV
100 eV
1 keV
10 keV
Photon energy

Simple picture:

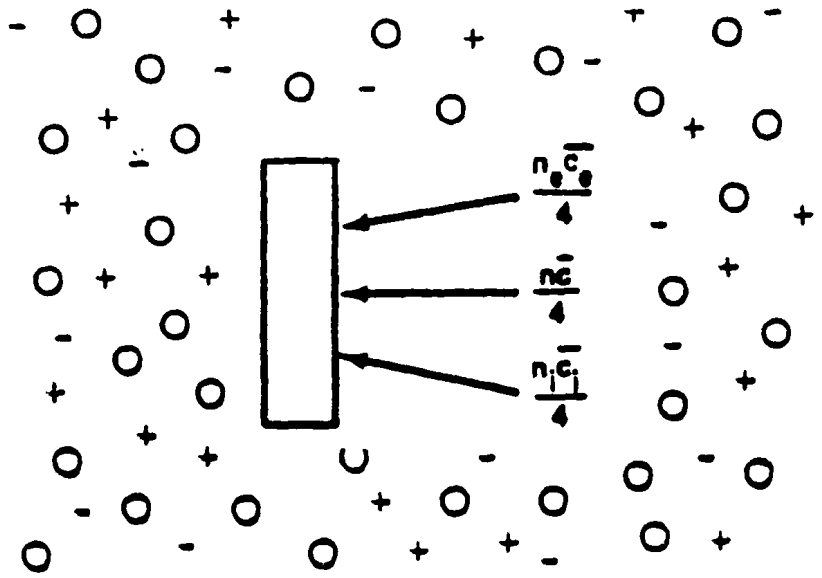
- Electron gas in thermal equilibrium
- Ion Gas in thermal equilibrium
- Neutral gas (obviously) in thermal equilibrium

For the three systems we define the energy distribution function.
So we define an average energy (average temperature T, T_i, T_e)

For electron the average energy is 1 to 10 eV
For gas and ions is of order of 0.1 eV.

A non perturbed plasma is defined by the condition Ni=Ne

Typical values of Ni and Ne are in the range 10^8 to 10^{12} ions(electrons)/cm^3



Initial particle fluxes at the substrate

Neutrals

$m = 6.6\ 10^{-23}$g

$T = 20^{\circ}C = 293K \equiv 1/40eV$

$\bar{c} = 4.0\ 10^{4}$ cm/sec

Ions

$m_i = 6.6\ 10^{-23}$g

$T_i = 500K \equiv 0.04eV$

$\bar{c}_i = 5.2\ 10^{4}$ cm/sec

Electrons

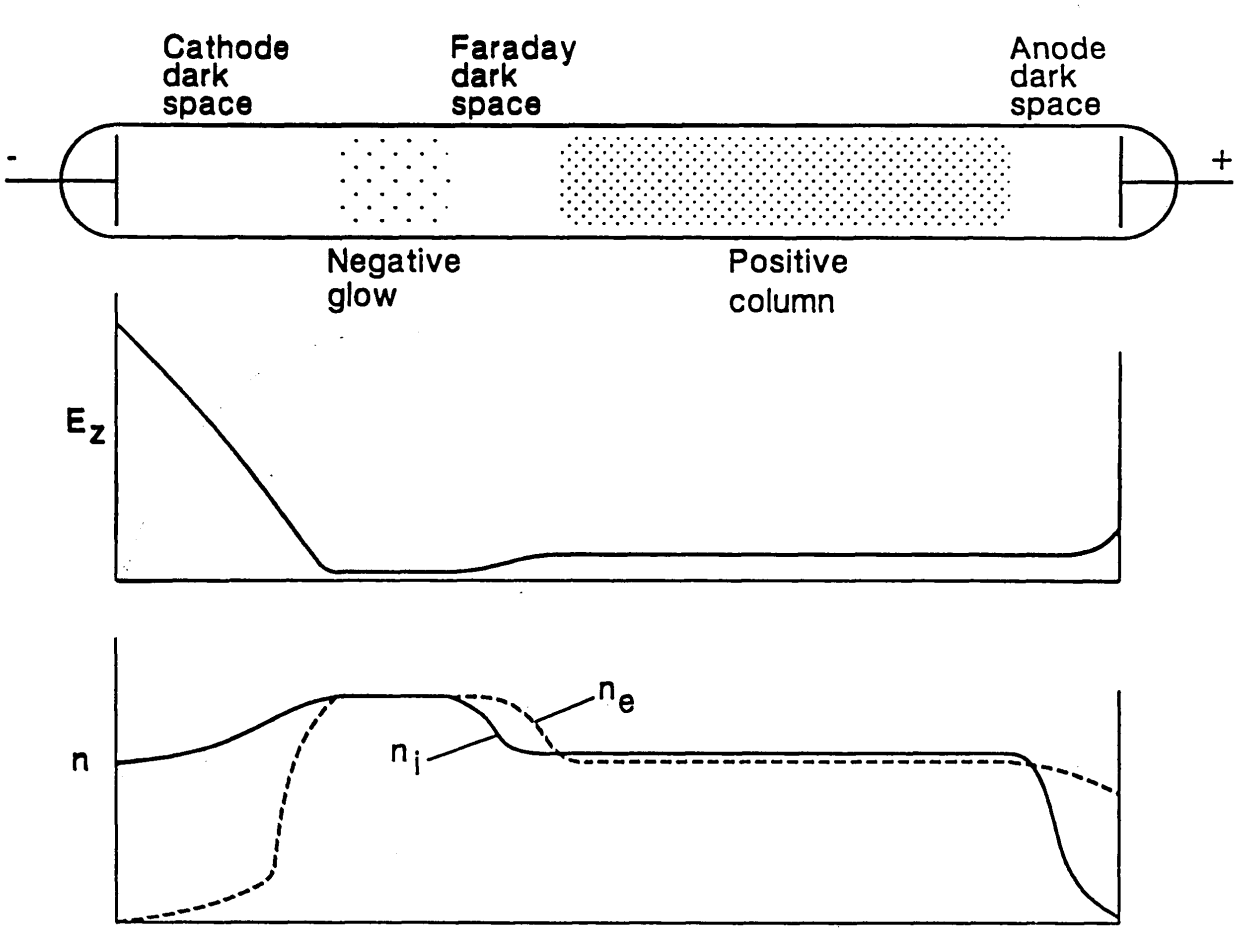
$m_e = 9.1\ 10^{-28}$g

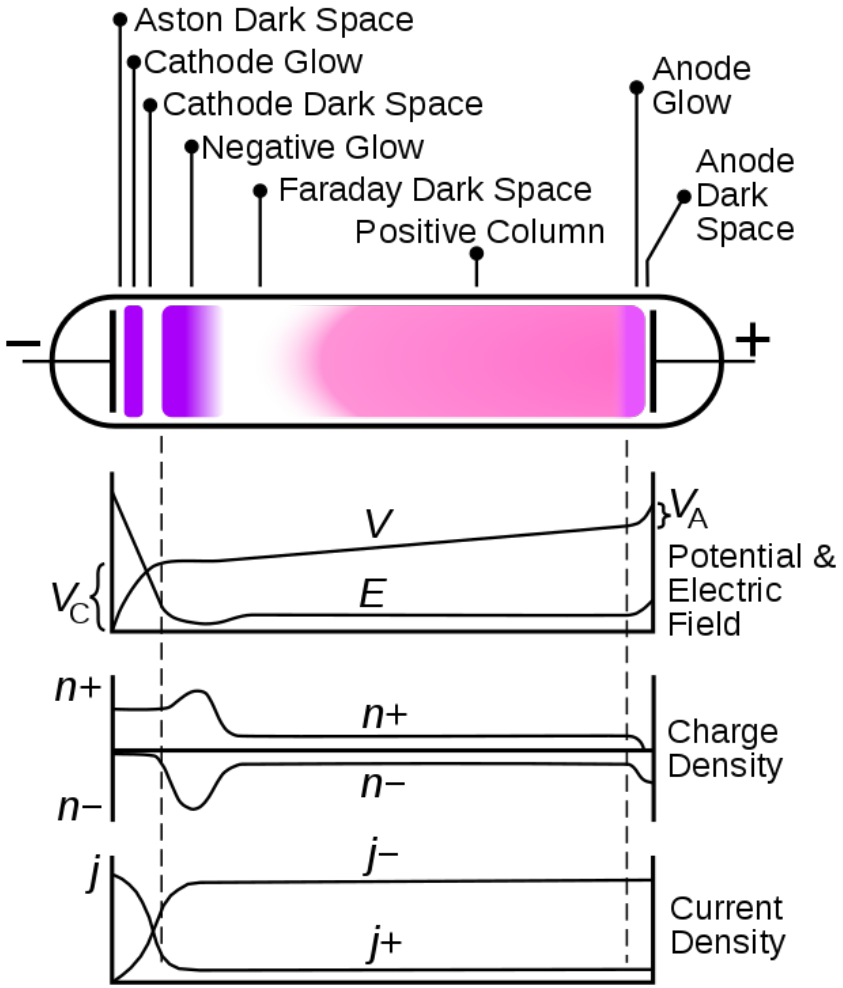
$T_e = 23\,200K \equiv 2eV$

$\bar{c}_e = 9.5\ 10^{7}$ cm/sec

$$\bar{c} = \left(\frac{8kT}{\pi m}\right)^{1/2}$$

Plasma Ignition between two electrodes in a rarefied gas

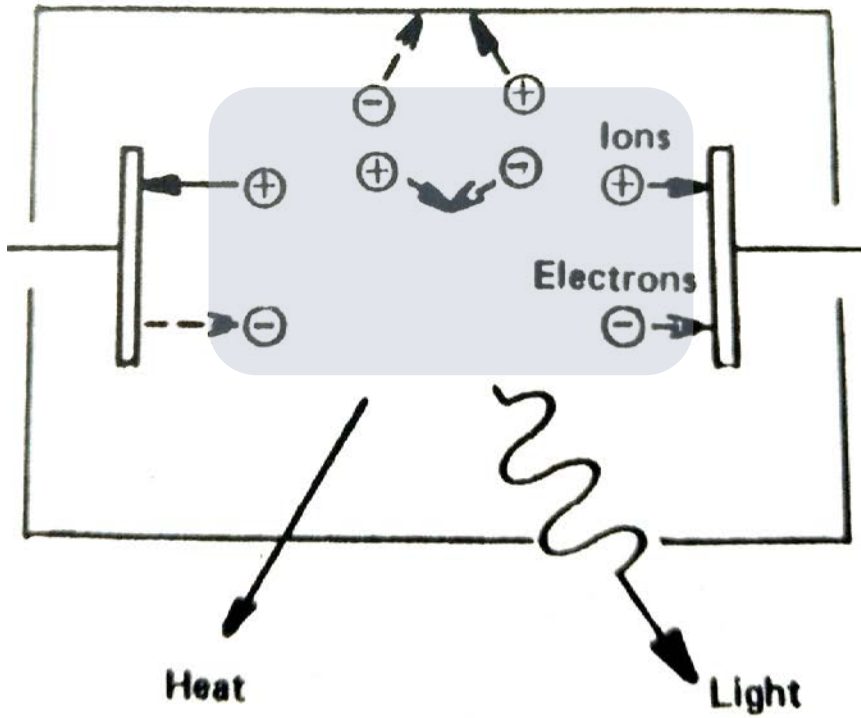




CATODO

Es: -500V

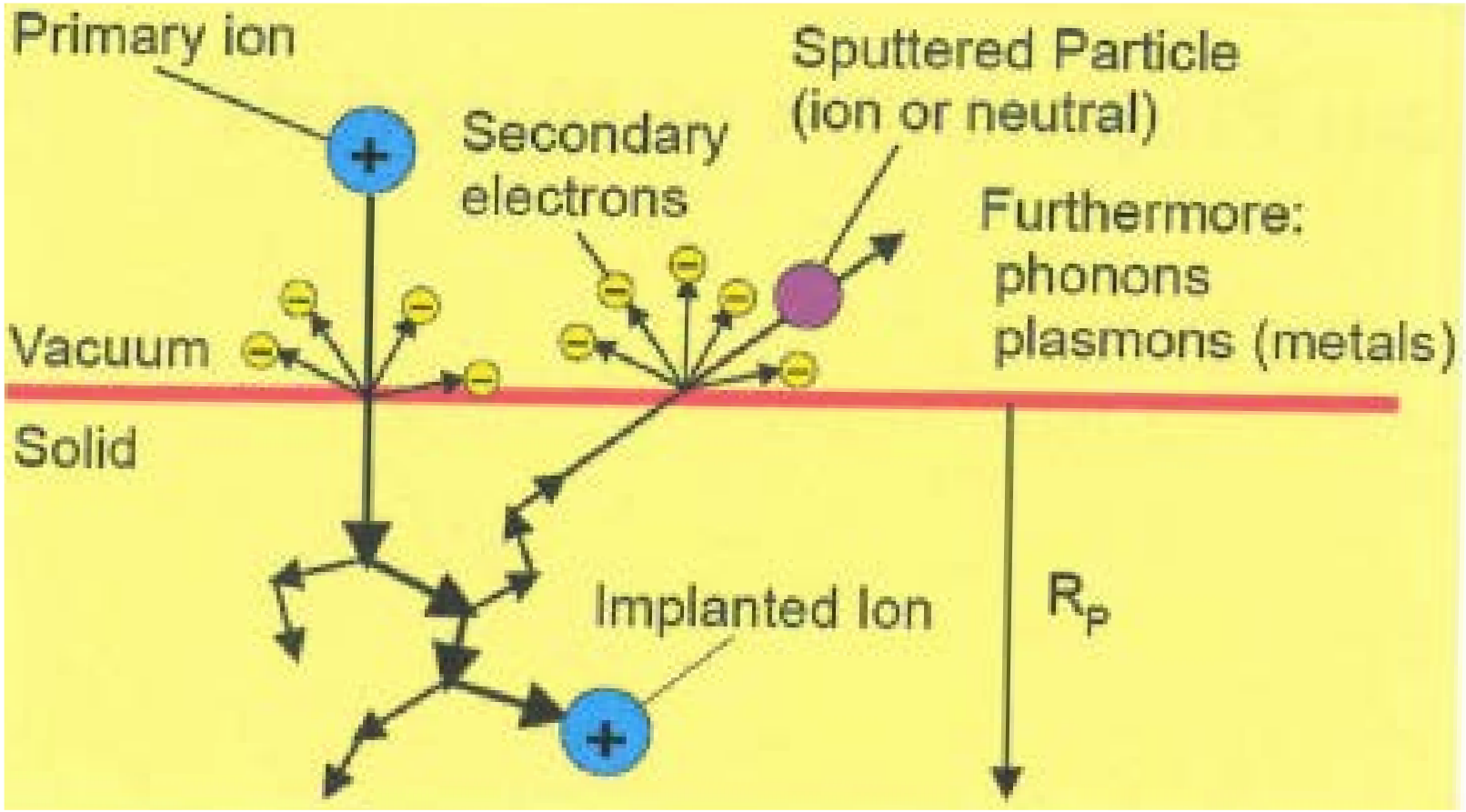
Rispetto massa



ANODO

COME USARE UN PLASMA PER DEPOSITARE MATERIALI INNOVATIVI (… E TRADIZIONALI)

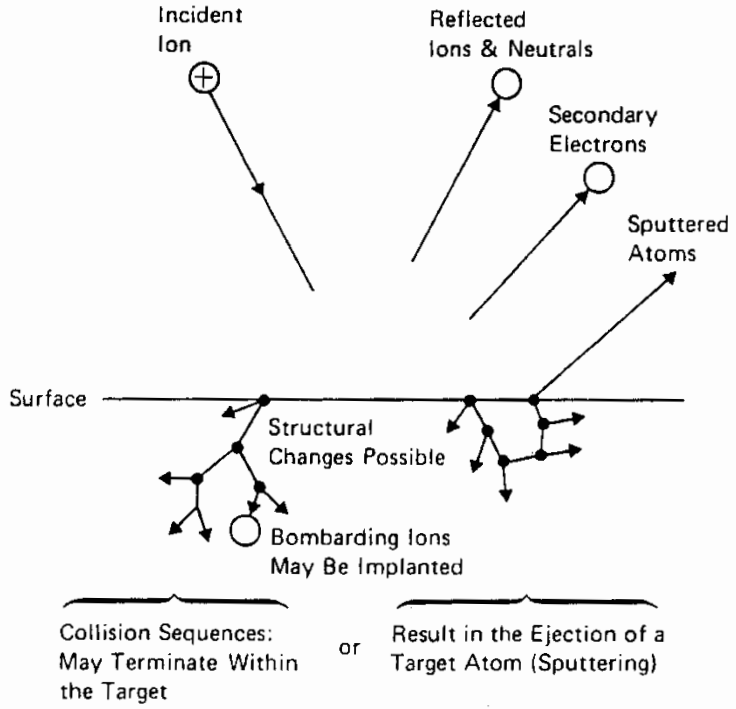
IL FENOMENO FISICO DI SPUTTERING

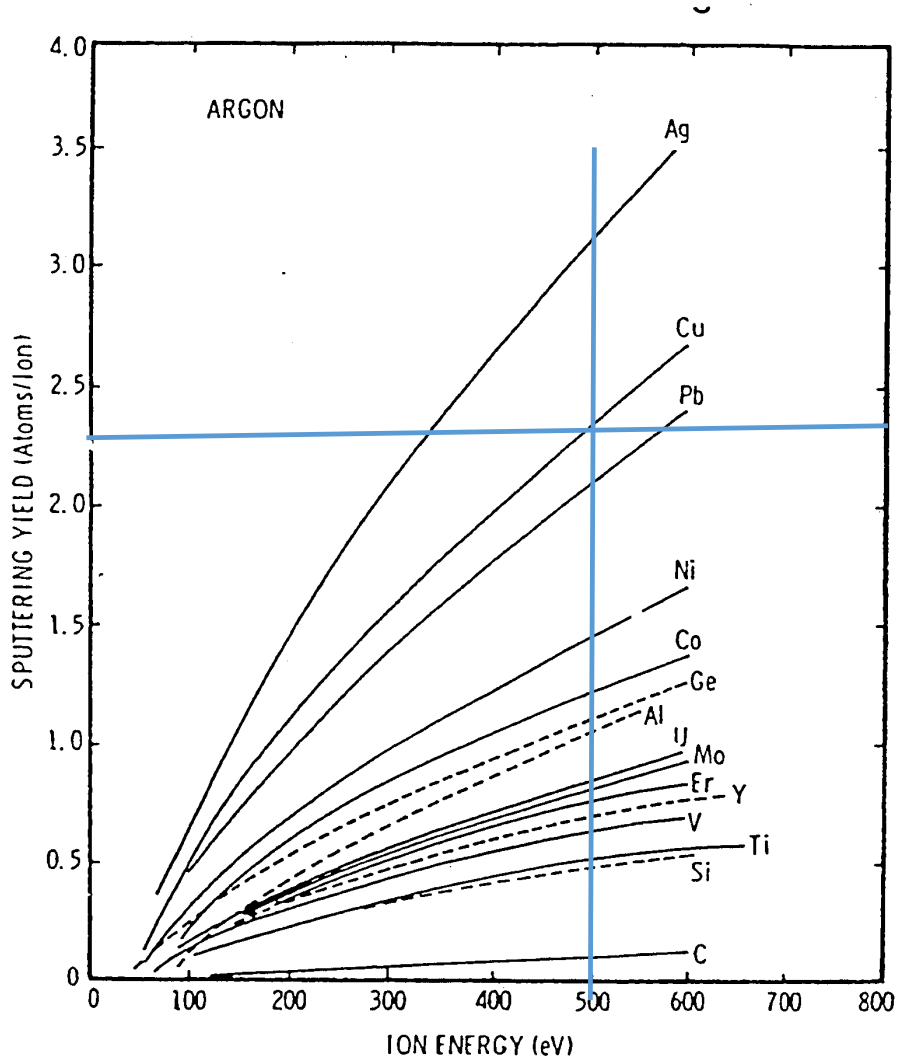


Sputtering: basic phenomena and experimental data

What Is Sputtering?

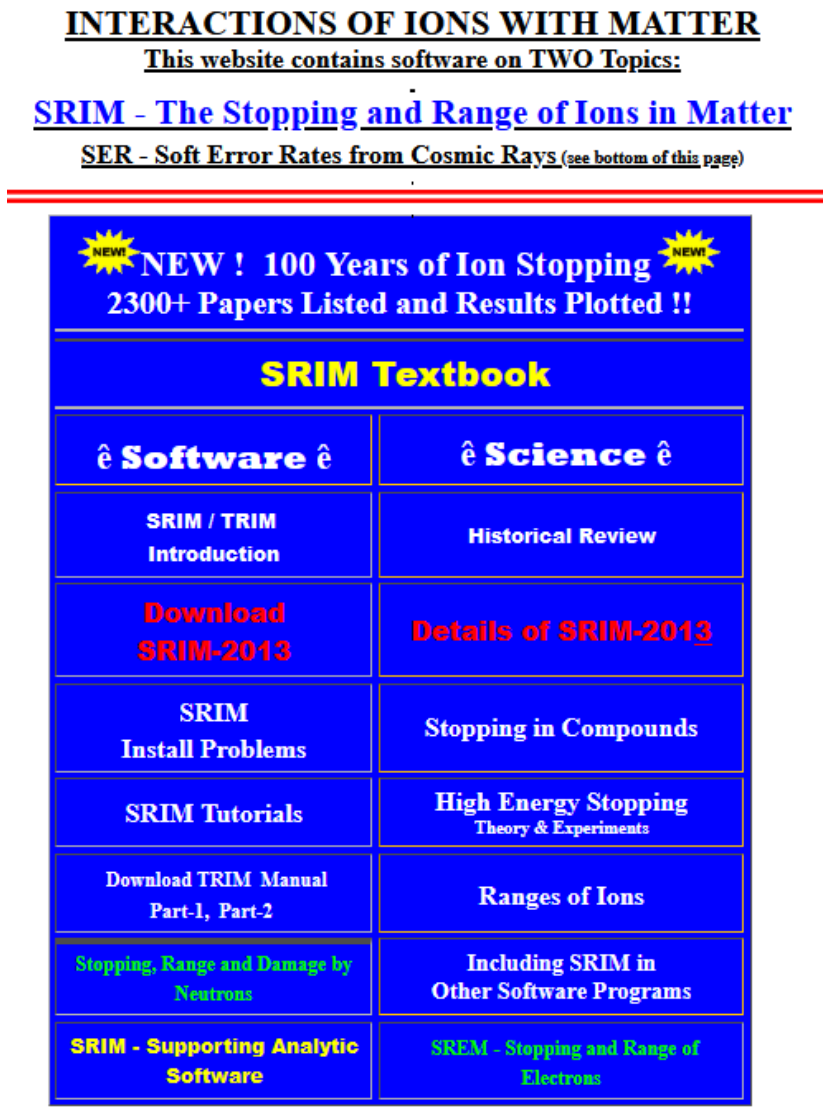
Sputtering is a process operating on an atomic or molecular scale whereby an atom or molecule of a surface is ejected when the surface is struck by a fast incident particle (Figure 2). The process of sputtering is reasonably well understood. The momentum of the incident atom is transferred to the atoms in the target material and this momentum transfer can often lead to the ejection of a surface atom – the sputtering process. The process is often likened to a game of atomic snooker since the scattering process employs similar mechanics.





MONTE CARLO TRIM CALCULATION

- http://srim.org/



INTERACTIONS OF IONS WITH MATTER

This website contains software on TWO Topics:

SRIM - The Stopping and Range of Ions in Matter

SER - Soft Error Rates from Cosmic Rays (see bottom of this page)

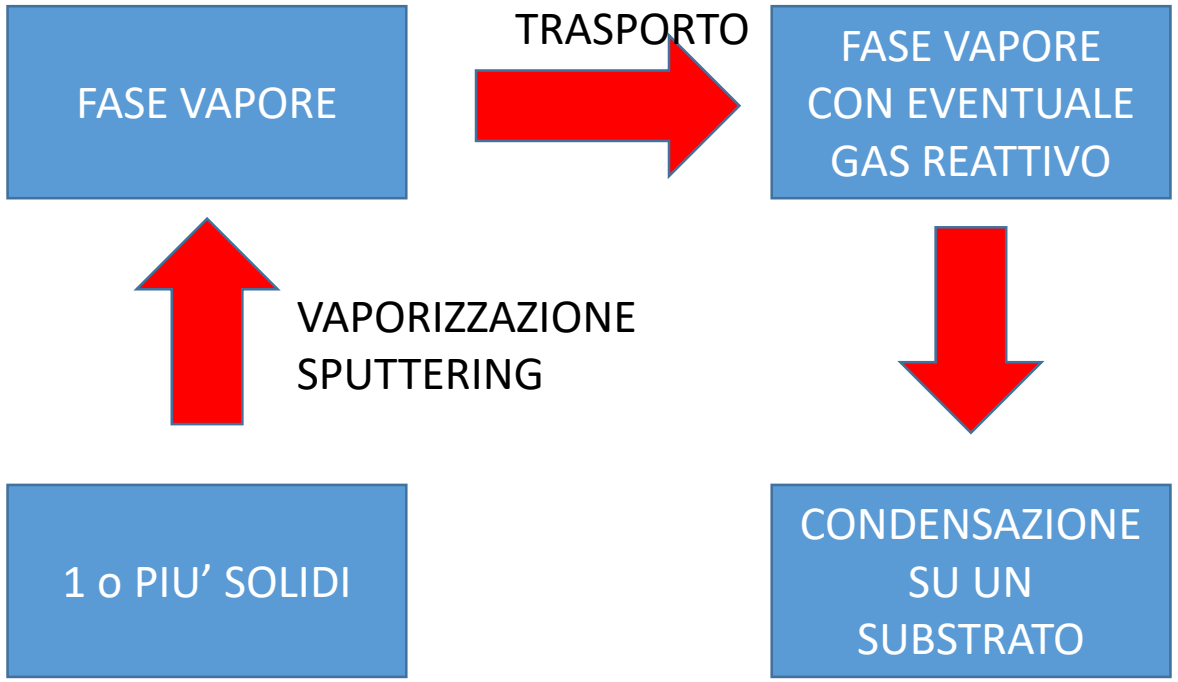
NEW ! 100 Years of Ion Stopping

2300+ Papers Listed and Results Plotted !!

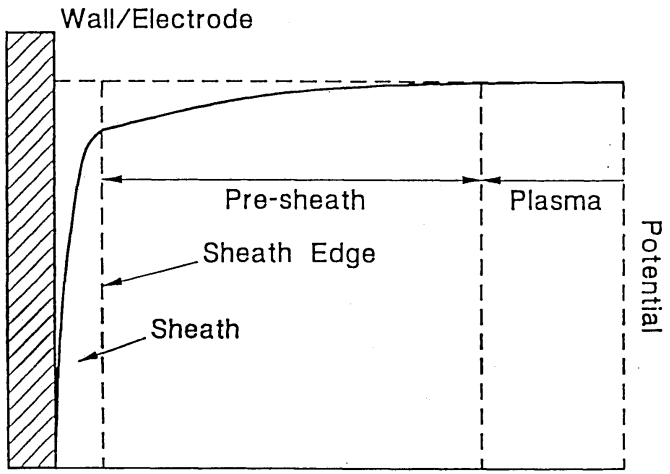
SRIM Textbook

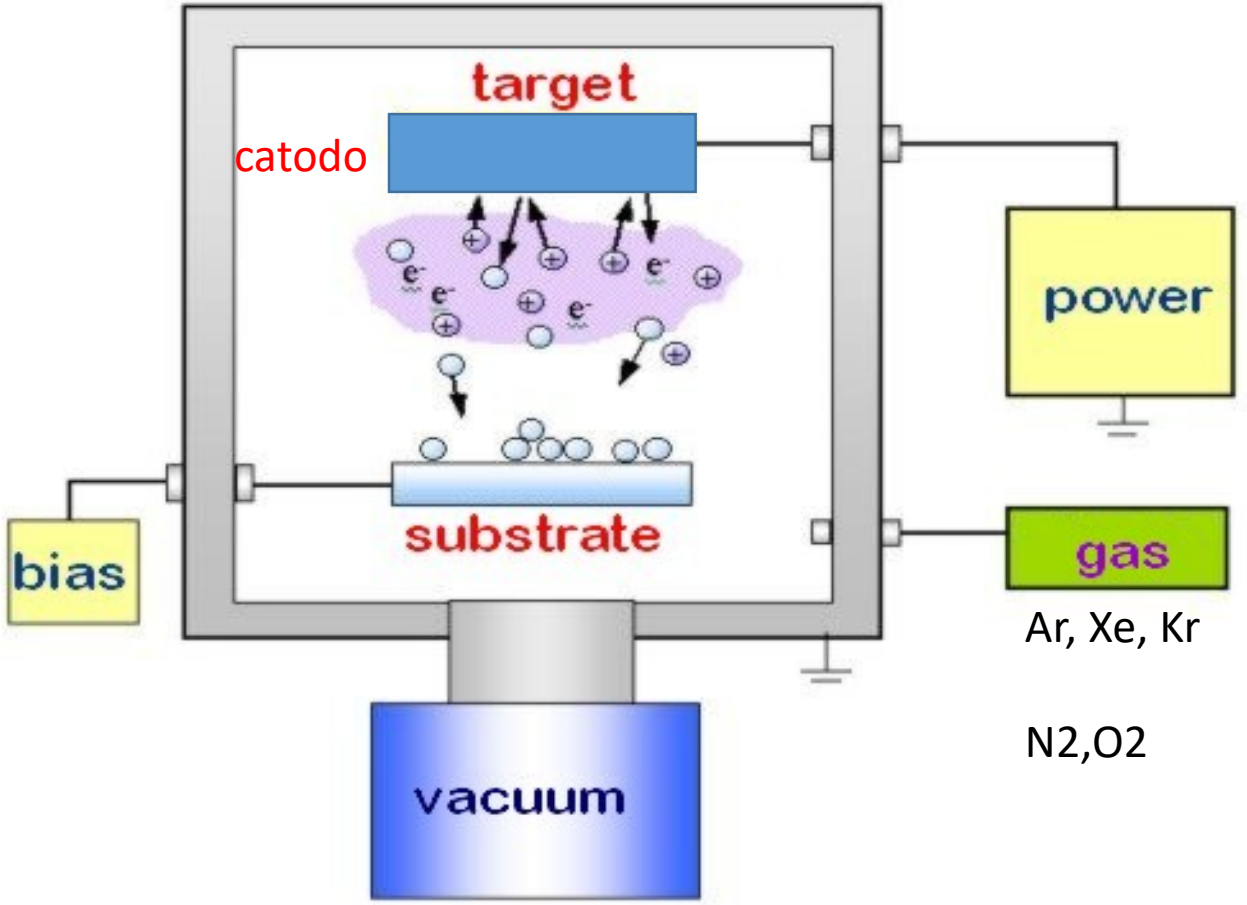
ê Software ê	ê Science ê
SRIM / TRIM Introduction	Historical Review
Download SRIM-2013	Details of SRIM-2013
SRIM Install Problems	Stopping in Compounds
SRIM Tutorials	High Energy Stopping Theory & Experiments
Download TRIM Manual Part-1, Part-2	Ranges of Ions
Stopping, Range and Damage by Neutrons	Including SRIM in Other Software Programs
SRIM - Supporting Analytic Software	SREM - Stopping and Range of Electrons

From solid to vapor and back



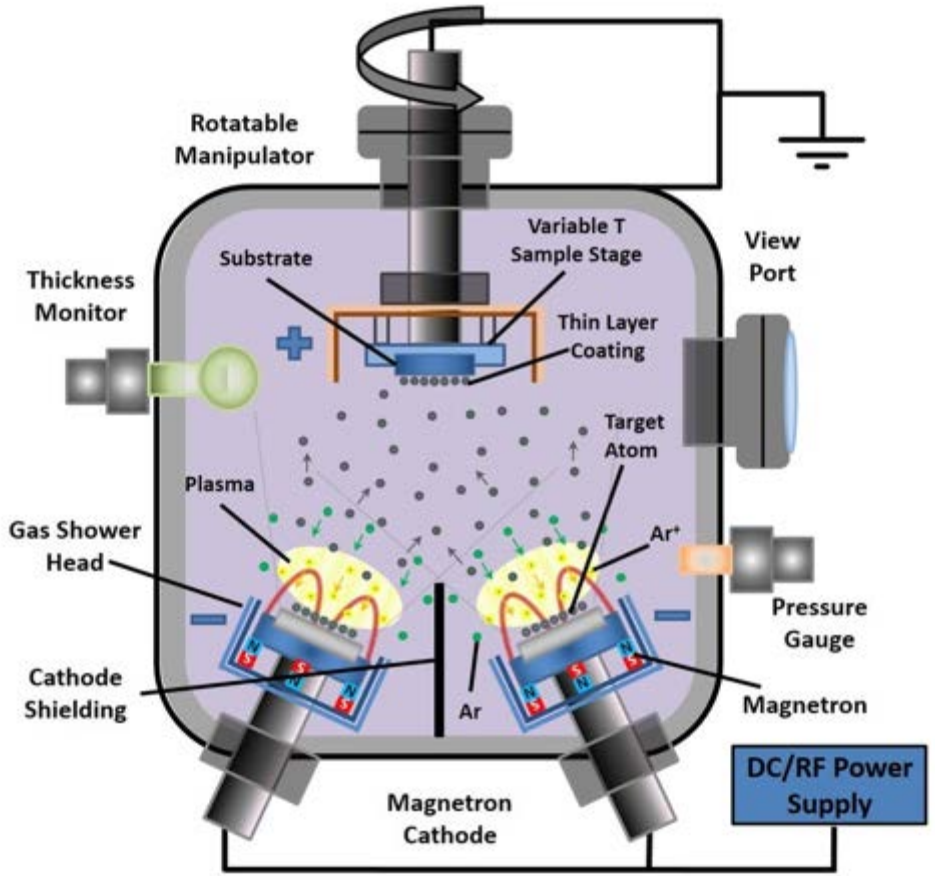
A simple sputtering system

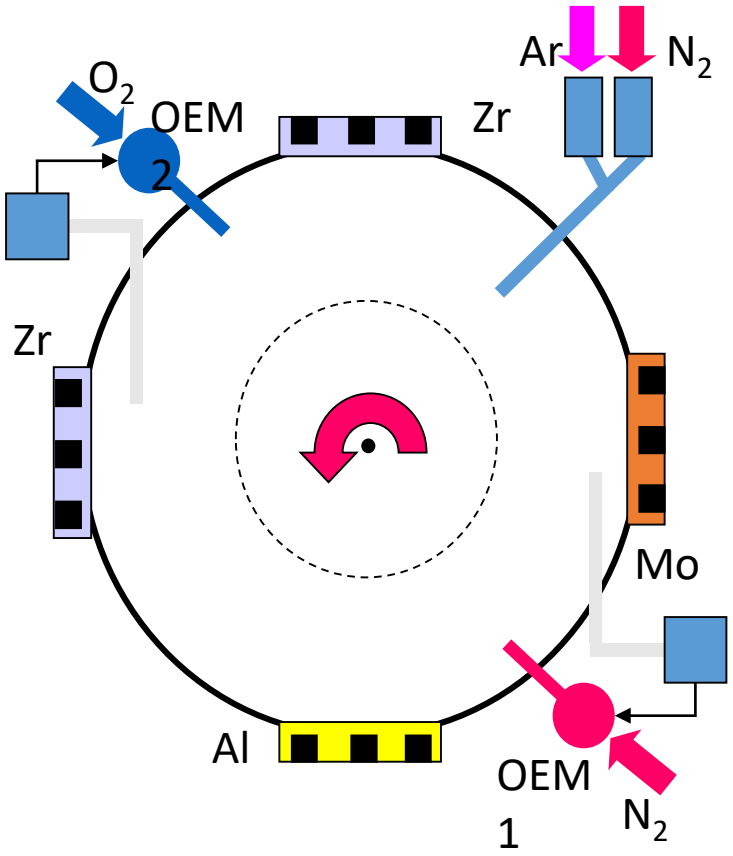




Ar, Xe, Kr

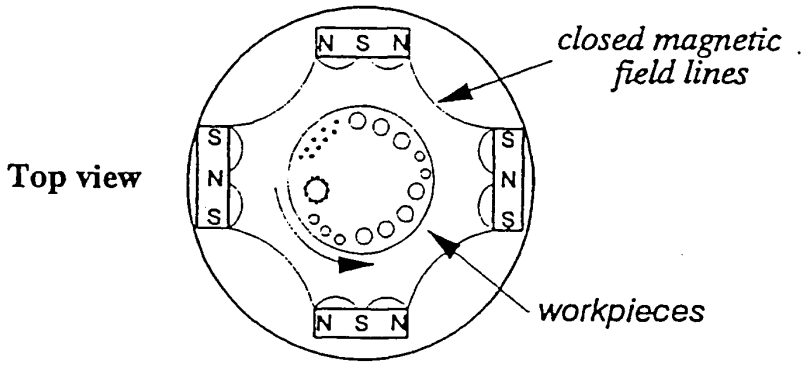
N2,O2

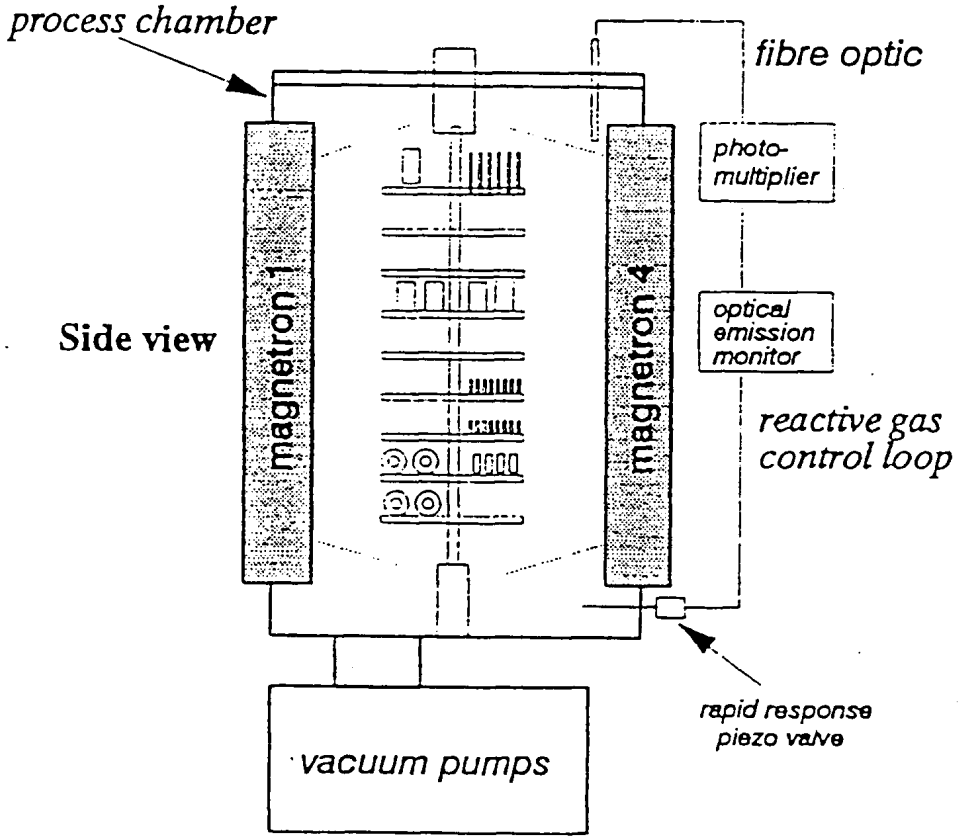

Rotatable
Manipulator
Variable T
Sample Stage
Substrate
View
Port
Thickness
Monitor
Thin Layer
Coating
Target
Atom
Plasma
Gas Shower
Head
Ar+
Pressure
Gauge
Cathode
Shielding
Ar
Magnetron
DC/RF Power
Supply
Magnetron
Cathode



Teer Coatings (UK)

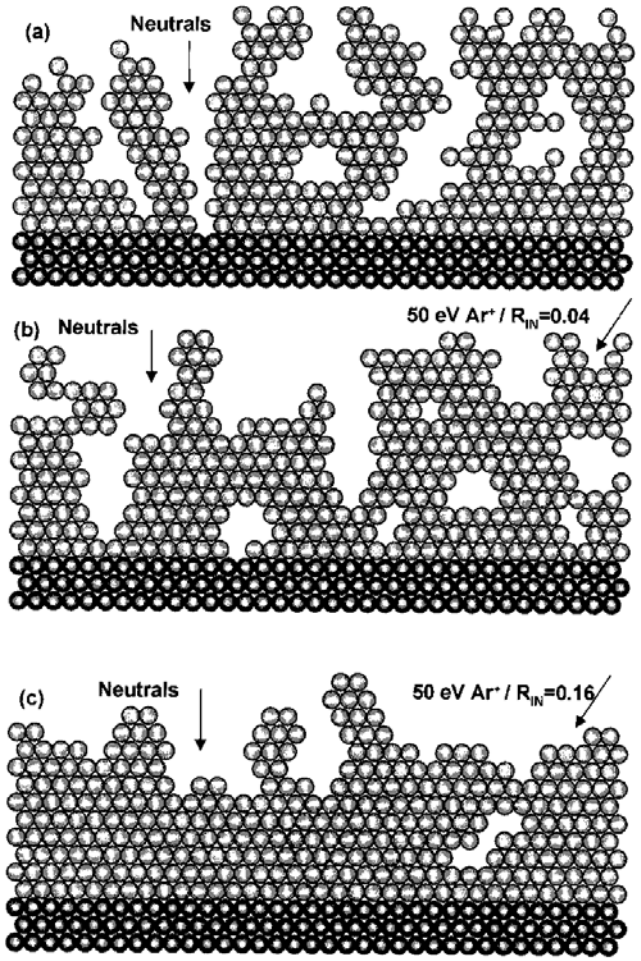
4 TARGETS CLOSED FIELD SYSTEM



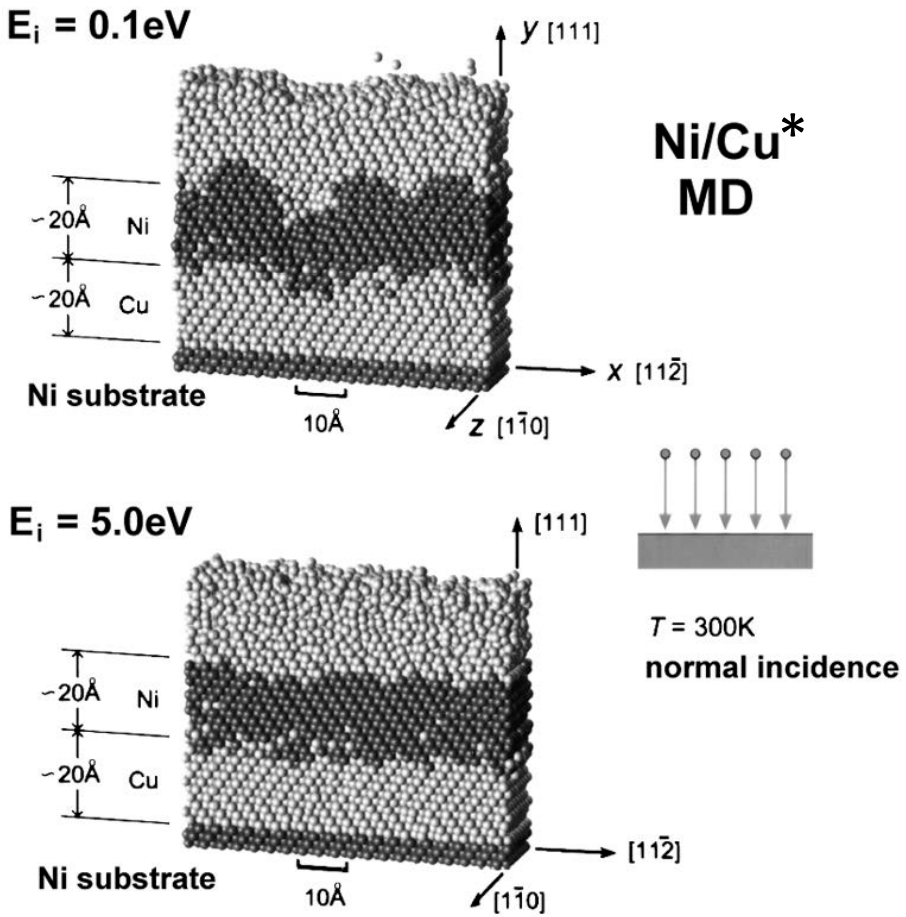


Deposition of Thin Films by sputtering

Deposition of Thin Films by sputtering: Ion Assisted growth

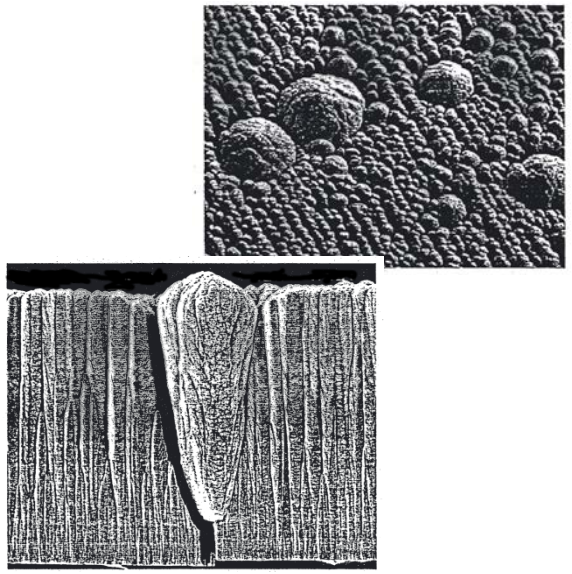


Morphology of a growing metal film as obtained from an early two-dimensional MD computer simulation using a Lennard-Jones interatomic potential, (*a*) without ion bombardment, (*b*) and (*c*) for IBAD using Ar^+ ions at E_i=50 eV and R_{in}=0.04 and 0.16, respectively. The directions of the incoming neutral and ion fluxes are indicated by arrows;



* X. W. Zhou and H. N. G. Wadley, Journal of Applied Physics **87**, 2273 (2000).

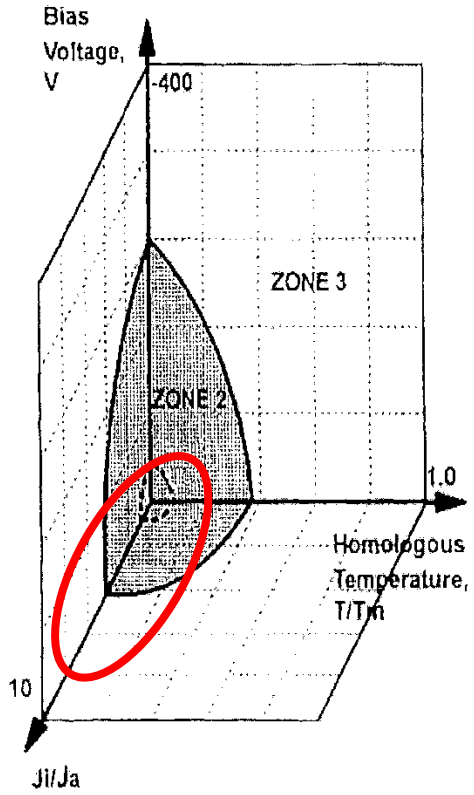
Deposition of Thin Films by sputtering: Highlights on film growth

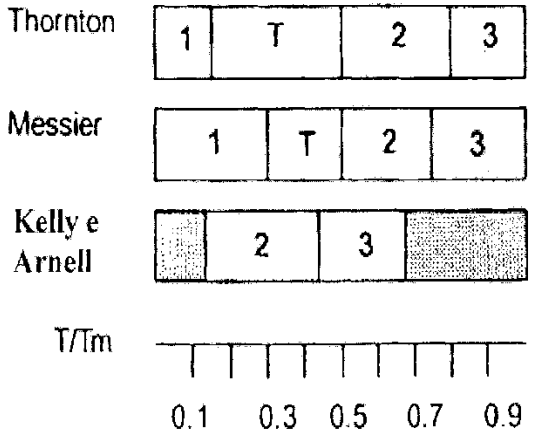


Effetto della temperatura

Effetto della pressione del gas

Effetto del bombardamento ionico a bassa energia

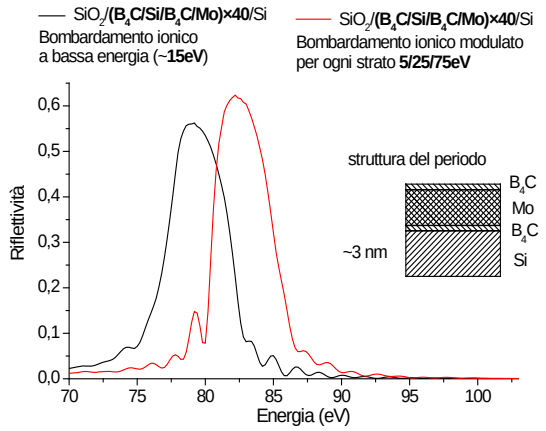




Multilayer Mirrors

- **Design and preparation of EUV and X-Ray High Reflectance Multilayer mirrors on flat and curved substrates for applications in astrophysics, lithography , "*water-window*" microscopy and Free Electron Laser Optics**

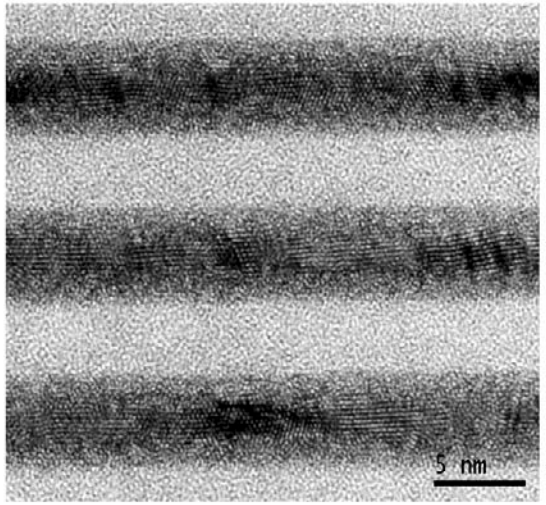
EUV Bragg High Reflectivity

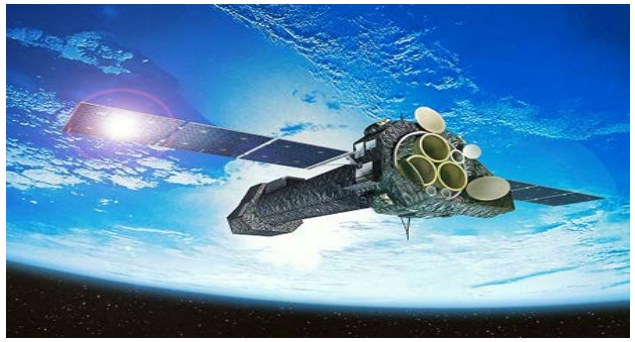


EUV lithography mirrors

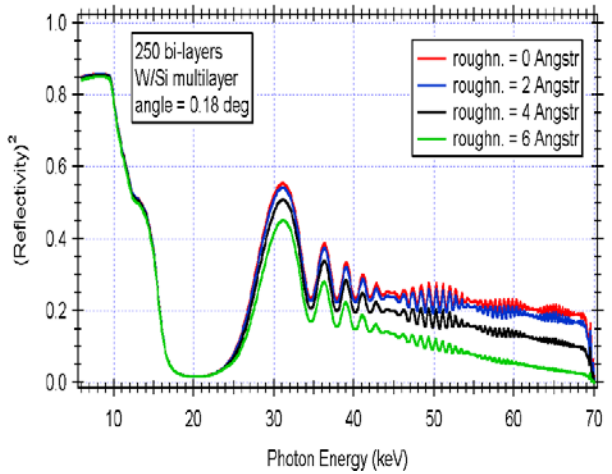
- **"*water-window*" microscopy**
- **Free Electron Laser Optics**
- **EUV Polarimeters**

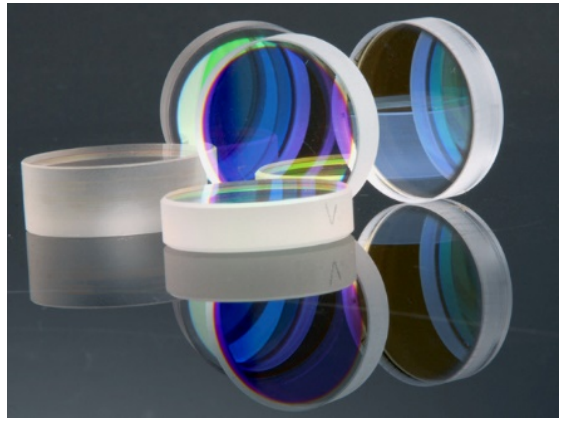
Multilayer Technology

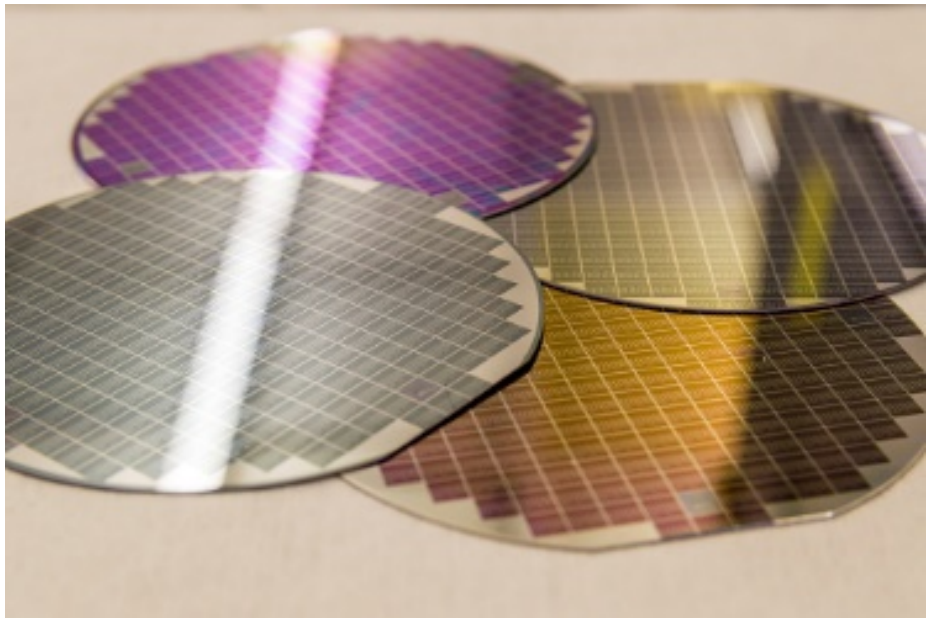




Supermirror design for hard X-ray telescopes (Simbol-X)



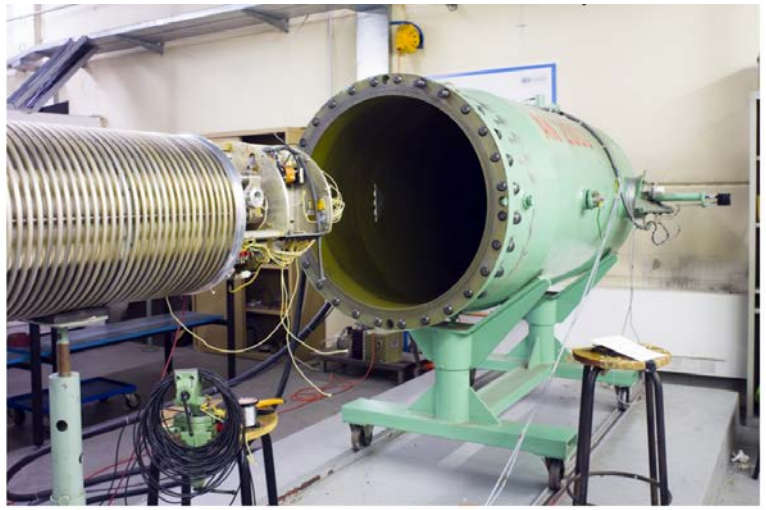


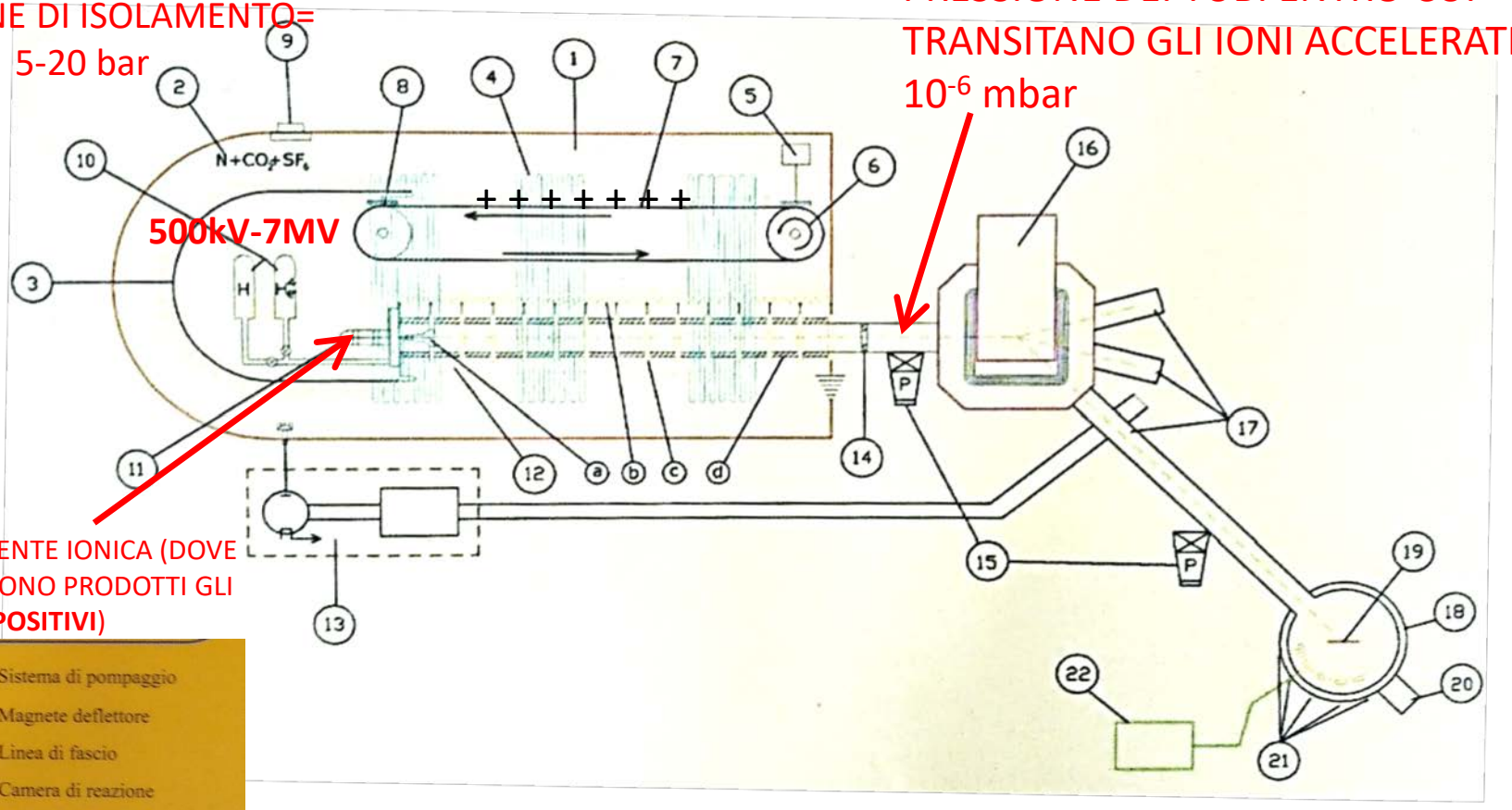


ACCELERATORE VAN DE GRAAFF

PRESSIONE DI ISOLAMENTO= 5-20 bar

PRESSIONE DEI TUBI ENTRO CUI TRANSITANO GLI IONI ACCELERATI: 10^{-6} mbar





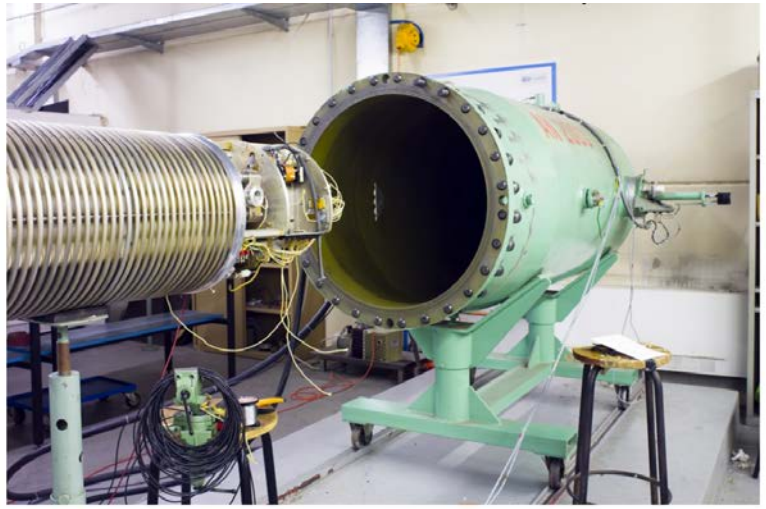
SORGENTE IONICA (DOVE VENGONO PRODOTTI GLI **IONI POSITIVI**)

1. Tank
2. Gas di riempimento
3. Testa (term. H.V.)
4. Anelli di sostegno
5. Alimentatore di cariche
6. Motore
7. Cinghia
8. Pettine (Elettrodo di scarica)
9. Voltmetro
10. Ampolle di gas
11. Sorgenti di ioni
12. Tubo acceleratore con:
    - a. Elettrodo di fuoco
    - b. Partitore di tensione
    - c. Anelli focalizzanti
    - d. Elementi isolanti
13. Sistema di stabilizzazione
14. Anello di Fuoco
15. Sistema di pompaggio
16. Magnete deflettore
17. Linea di fascio
18. Camera di reazione
19. Bersaglio
20. Pozzo di Faraday
21. Rivelatori
22. Acquisizione dati

MICROANALISI
IMPIANTAZIONE IONICA
LITOGRAFIA IONICA
IRRAGGIAMENTI

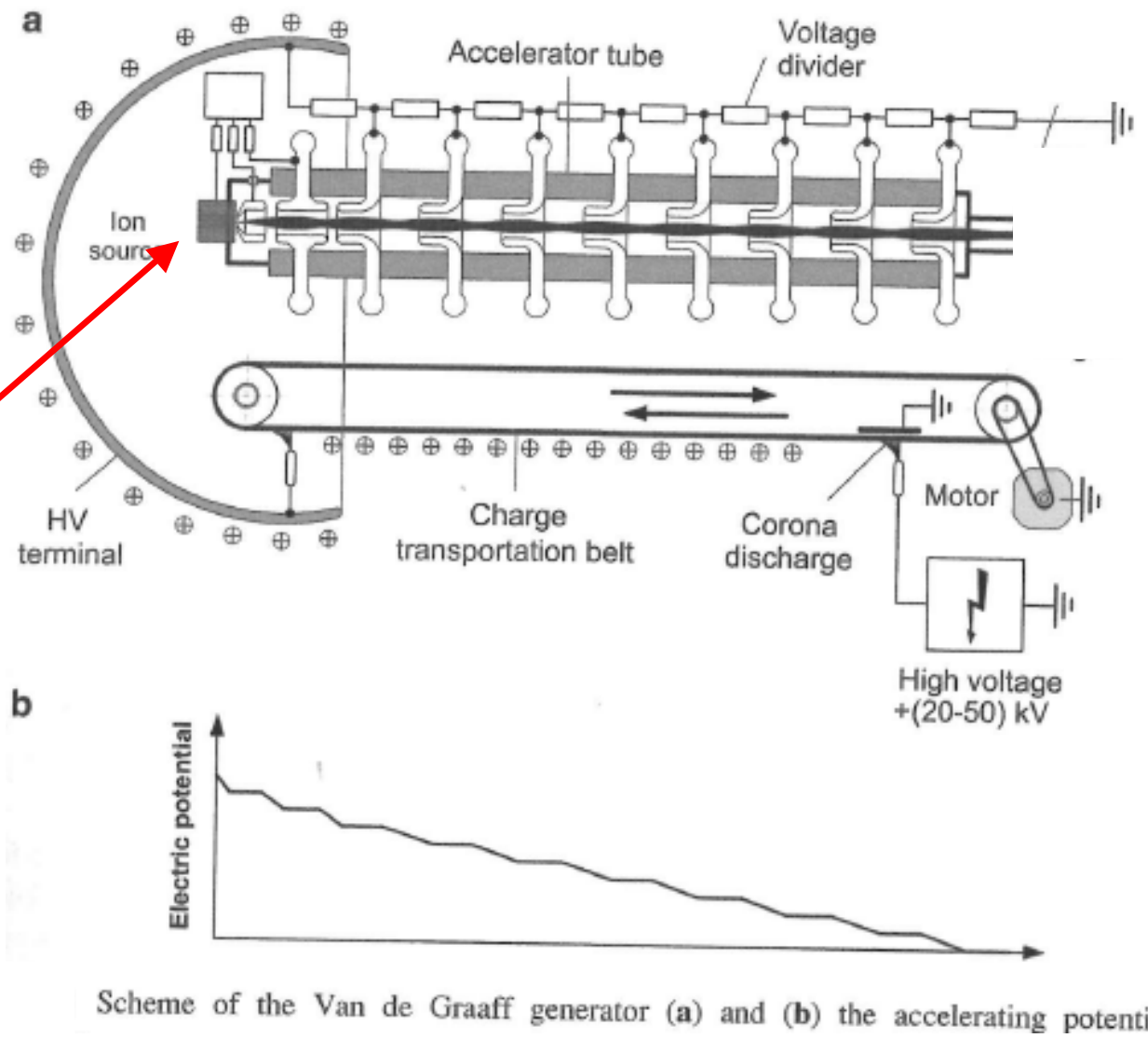
ACCELERATORE VAN DE GRAAFF

PRESSIONE DI ISOLAMENTO= 5-20 bar

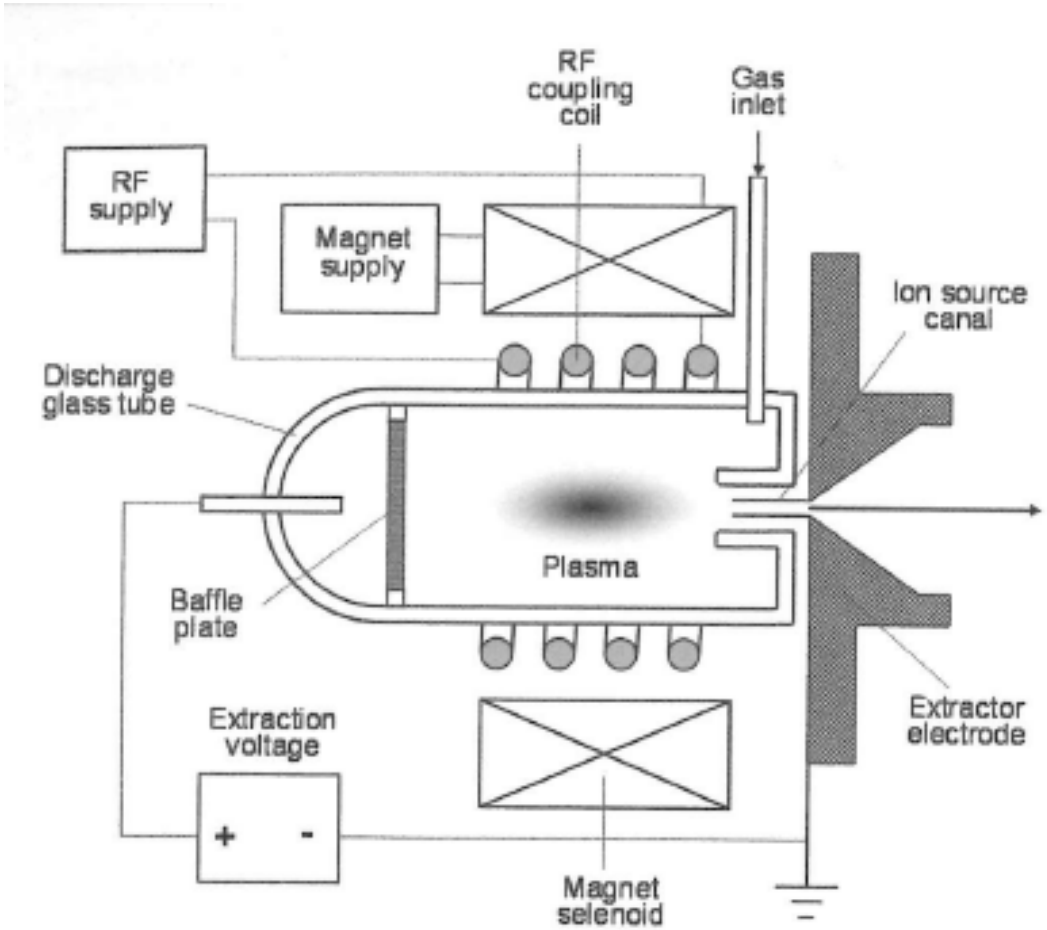


500kV-7MV

SORGENTE IONICA (DOVE VENGONO PRODOTTI GLI **IONI POSITIVI**)



Scheme of the Van de Graaff generator (**a**) and (**b**) the accelerating potential

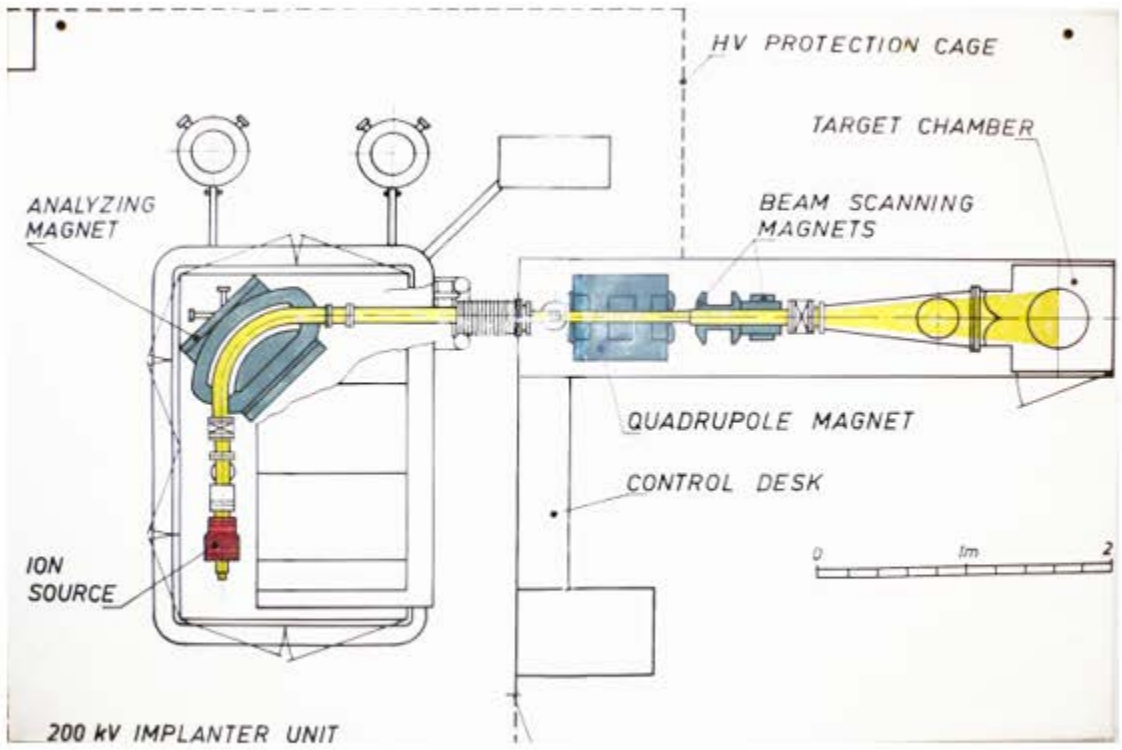


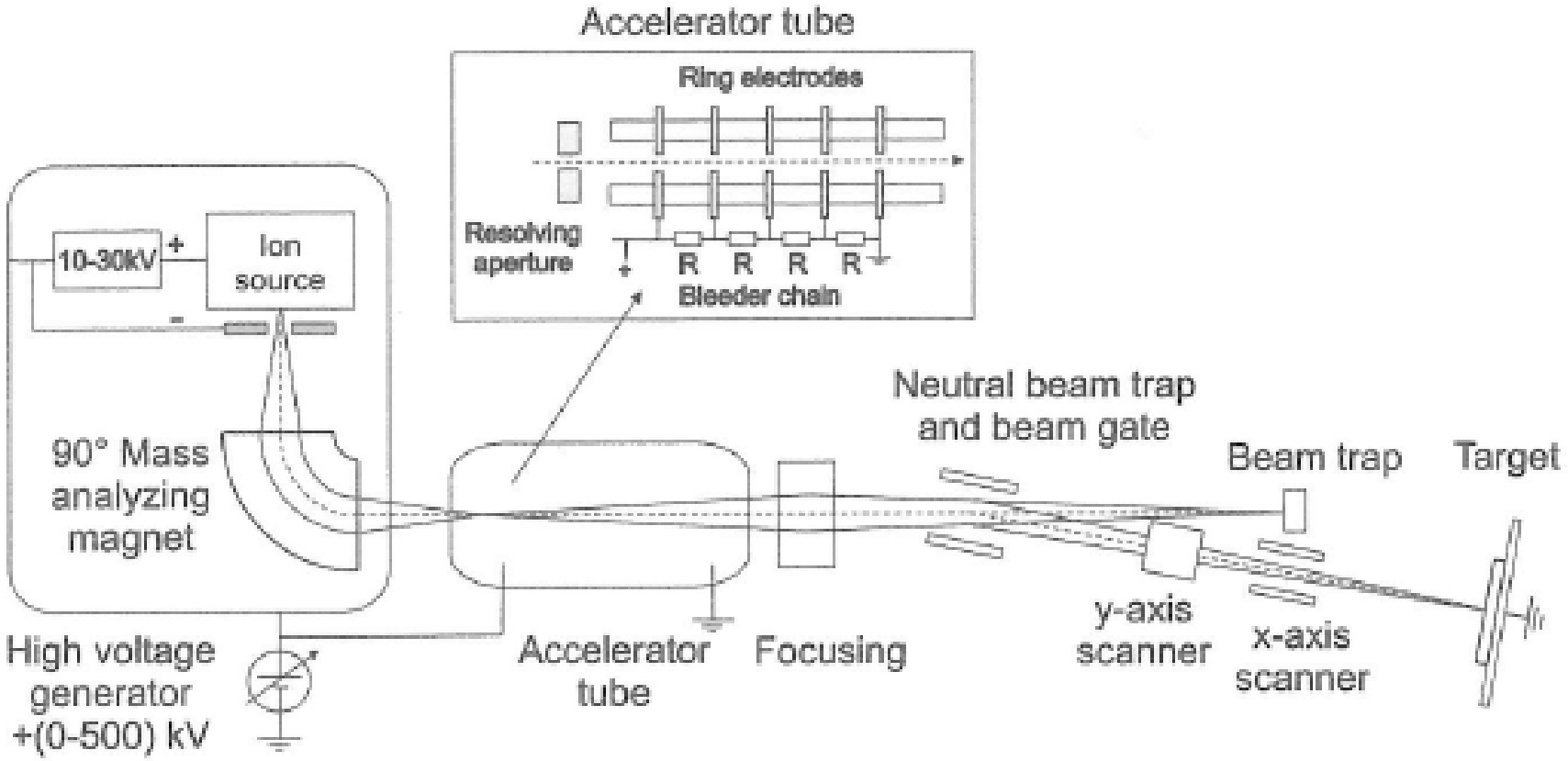
Principal buildup of a radio-frequency ion source

IMPIANTATORE IONICO

Ion Implantation (V<200KV)

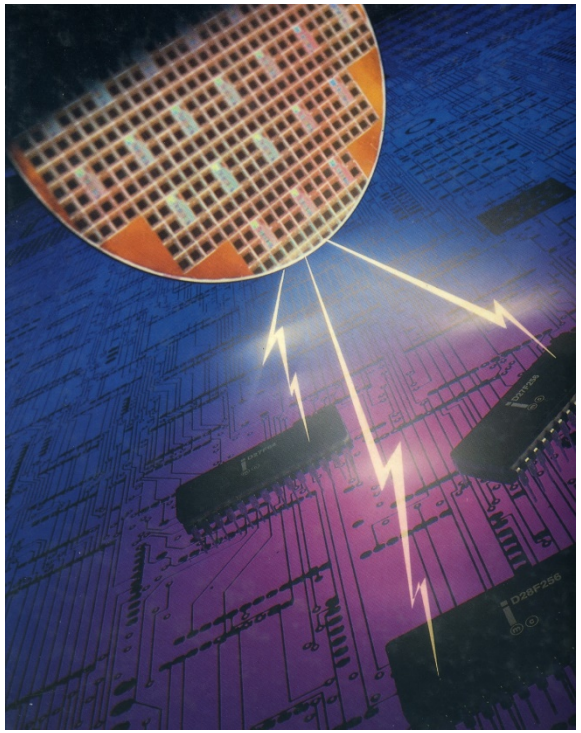
- Surface modification (H, Ar, Xe…)
- Doping of semiconductor
- Metal ions implantation (Au, Ag, Cu, Ga, Ni, Co, Fe, N, As ..)
  - optical properties
  - nano-clusters
  - alloys formation
- ion mixing





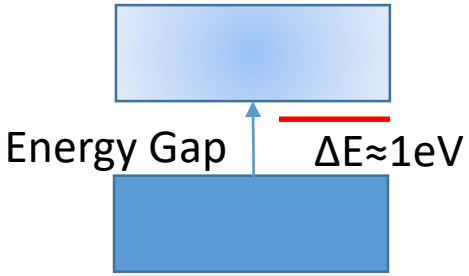
Principal technical buildup of low energy ion accelerators (ion implanter)

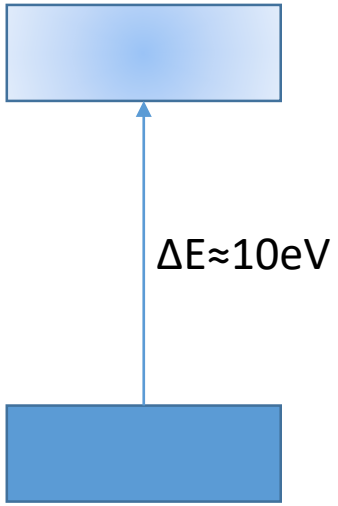
SEMICONDUTTORI (CENNI)



Resistività (Ωcm)	Materiale
$\rho < 10^{-3}$	Metalli
$10^{-3} < \rho < 10^{5}$	Semiconduttori
$\rho > 10^{5}$	Isolanti

SOLIDI CRISTALLINI





CONDUTTORI

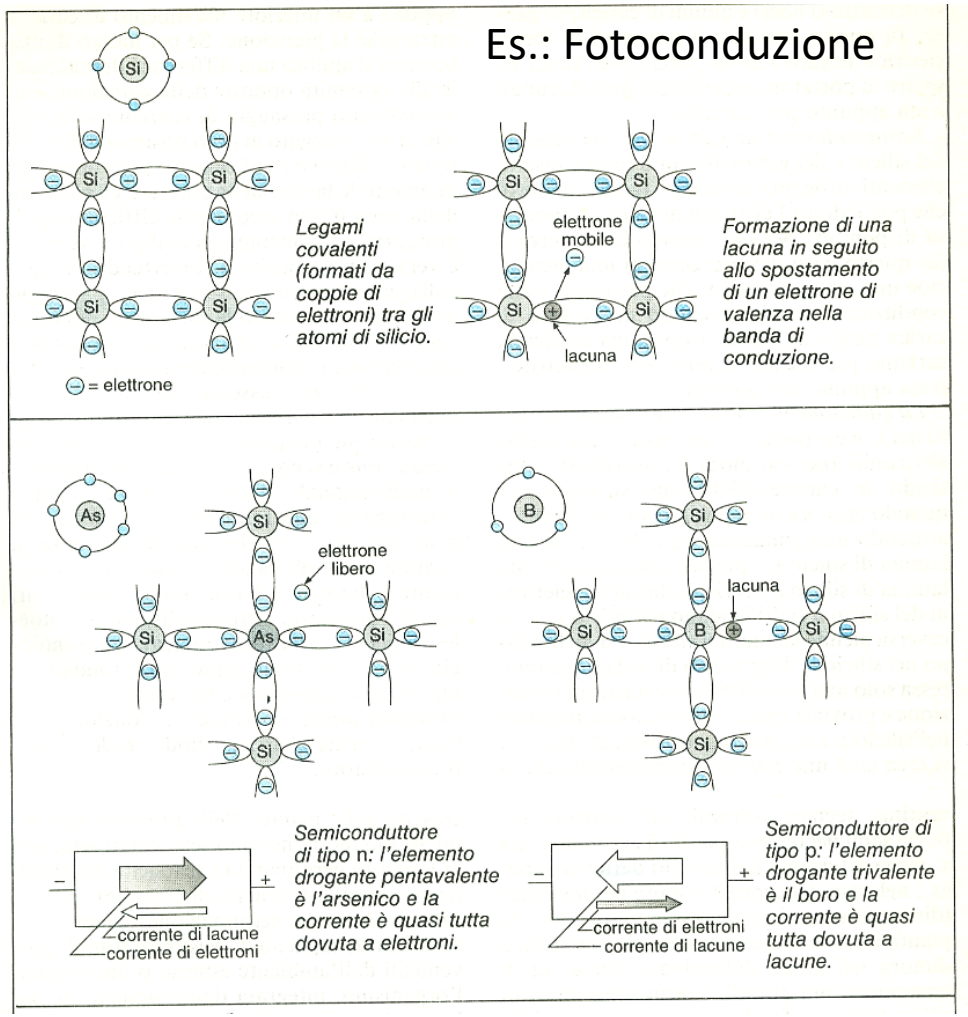
Appartengono a questa categoria tutti i metalli, come, ad esempio, rame (Cu), argento (Ag), Alluminio (Al). Sono ottimi conduttori sia di corrente che di calore e possiedono una struttura cristallina. La conducibilità elettrica diminuisce con la temperatura in un ampio range di temperature.

SEMICONDUTTORI

Le loro proprietà sono intermedie tra quelle dei conduttori e degli isolanti. Sono sostanze solide cristalline (come il Silicio, Germanio e Diamante) che offrono conducibilità crescente all'aumentare della temperatura. A temperatura ambiente manifestano proprietà di conduzione elettrica dovute ad impurezze perché elettroni possono passare alla banda di conduzione (per eccitazione termica 3/2kT o per fotoeccitazione= esposizione alla luce visibile). La conducibilità elettrica aumenta con la temperatura.
L'aggiunta di opportune impurità può esaltare la conduzione elettrica (drogaggio dei semiconduttori)

ISOLANTI

Lo sono principalmente solidi ionici e covalenti. In un isolante non esistono elettroni di valenza liberi di muoversi e tali da evidenziare un flusso di cariche ordinate, sotto l'azione di un campo elettrico. Queste sostanze sono definite isolanti perché offrono una resistenza assai grande al passaggio di cariche elettriche.



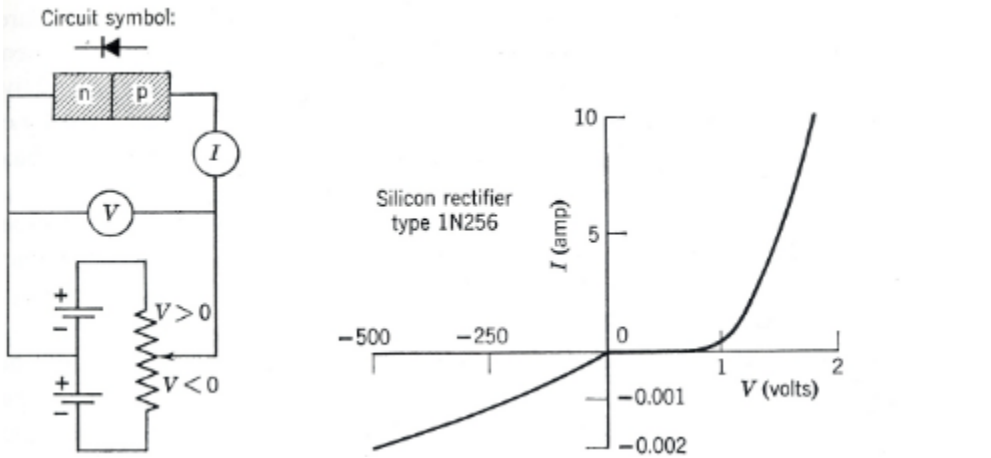
La caratteristica principale delle tecnologia dei circuiti integrati è il controllo della conducibilità elettrica del Silicio, ottenuta mediante la introduzione controllata di elementi elettricamente attivi nel reticolo cristallino.
Elementi della colonna III (come il Boro (B) o della colonna V (come il fosforo (P) e Arsenico (As) possono essere introdotti nel semiconduttore (colonna IV) nei siti reticolari. L'introduzione di detti atomi pentavaleti o trivalenti al posto di atomi (ad esempio) di silicio è conosciuta con il nome di DROGAGGIO:

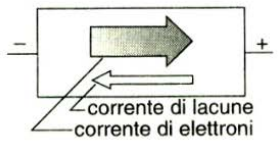
Impurezze che comportano una deficienza di elettroni rendono il semiconduttore di tipo P (positivo)

III	IV	V
5 B Boron	6 C Carbon	7 N Nitrogen
13 Al Aluminum	14 Si Silicon	15 P Phosphorus
31 Ga Gallium	32 Ge Germanium	33 As Arsenic

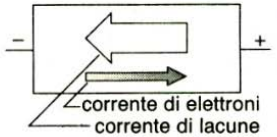
Impurezze che «donano» elettroni rendono il semiconduttore di tipo N (negativo)

DIODI E TRANSISTOR

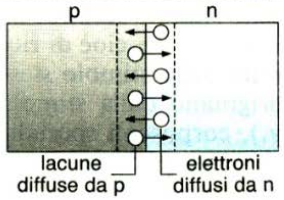




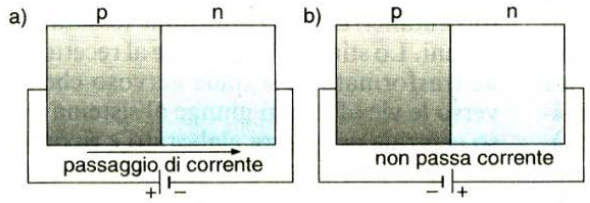
Semiconduttore di tipo n*: l'elemento drogante pentavalente è l'arsenico e la corrente è quasi tutta dovuta a elettroni.*



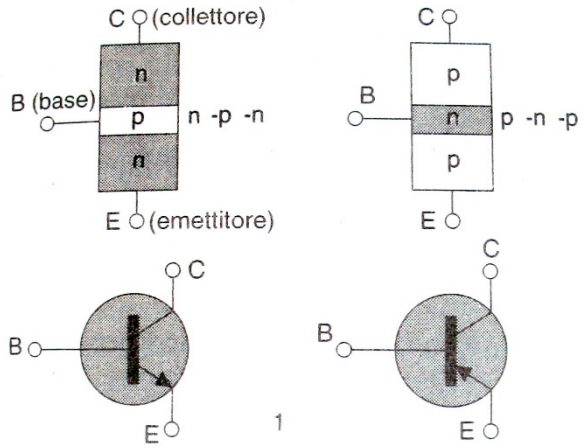
Semiconduttore di tipo p*: l'elemento drogante trivalente è il boro e la corrente è quasi tutta dovuta a lacune.*



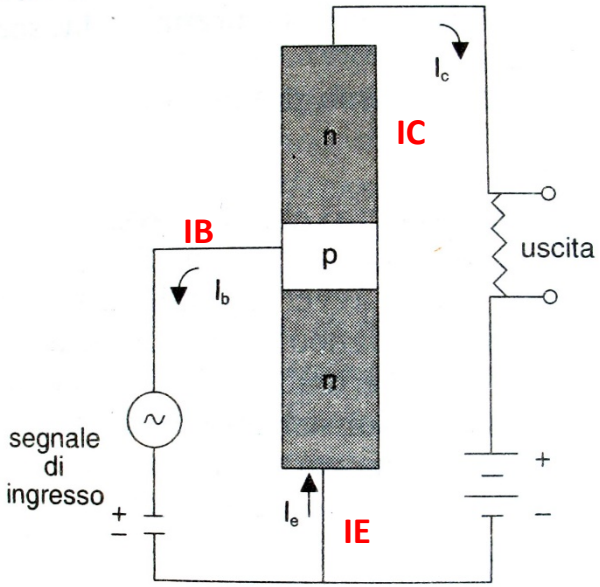
Nella giunzione p-n *la diffusione di elettroni va da* n *a* p*, mentre le lacune diffondono nel verso opposto: la diffusione è circoscritta alla zona di giunzione e termina quando la differenza di potenziale creata si oppone a ogni ulteriore diffusione di cariche.*



Un diodo a giunzione: il passaggio di corrente si ha solo se il semiconduttore p *è collegato al polo positivo della pila (a); viceversa, invertendo i collegamenti, non passa corrente (b).*



1



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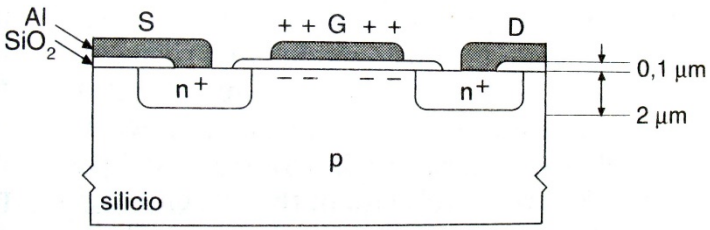
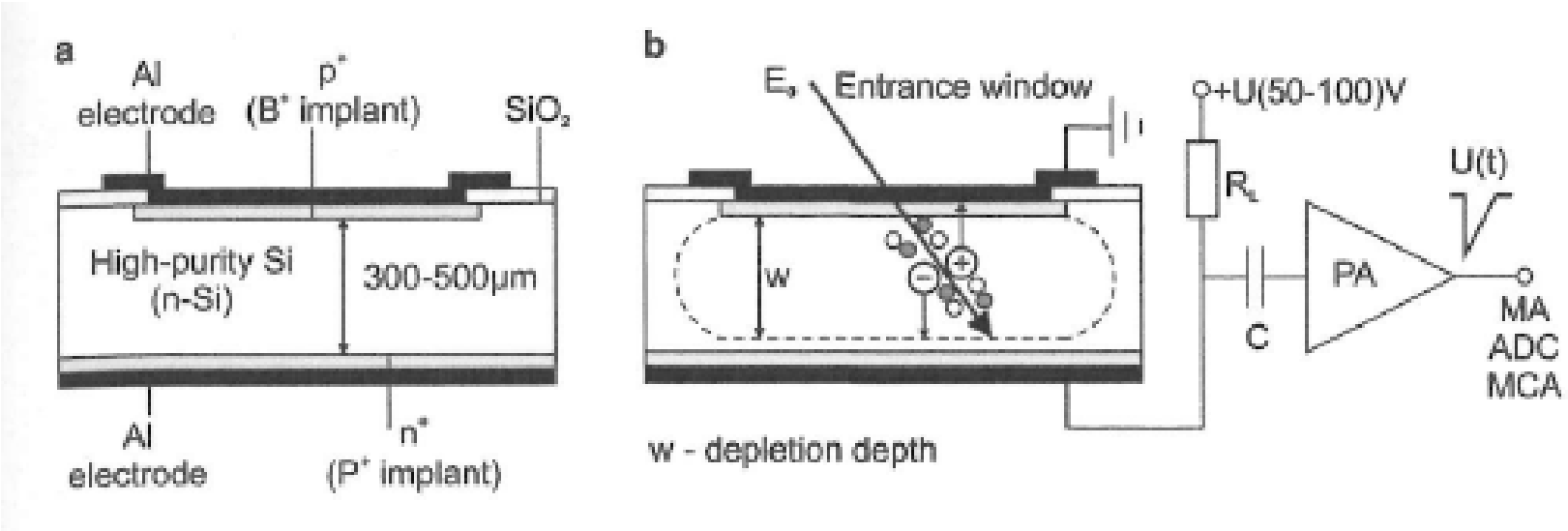
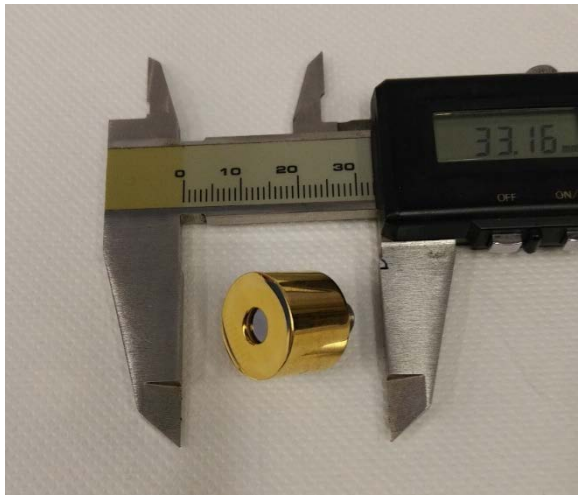
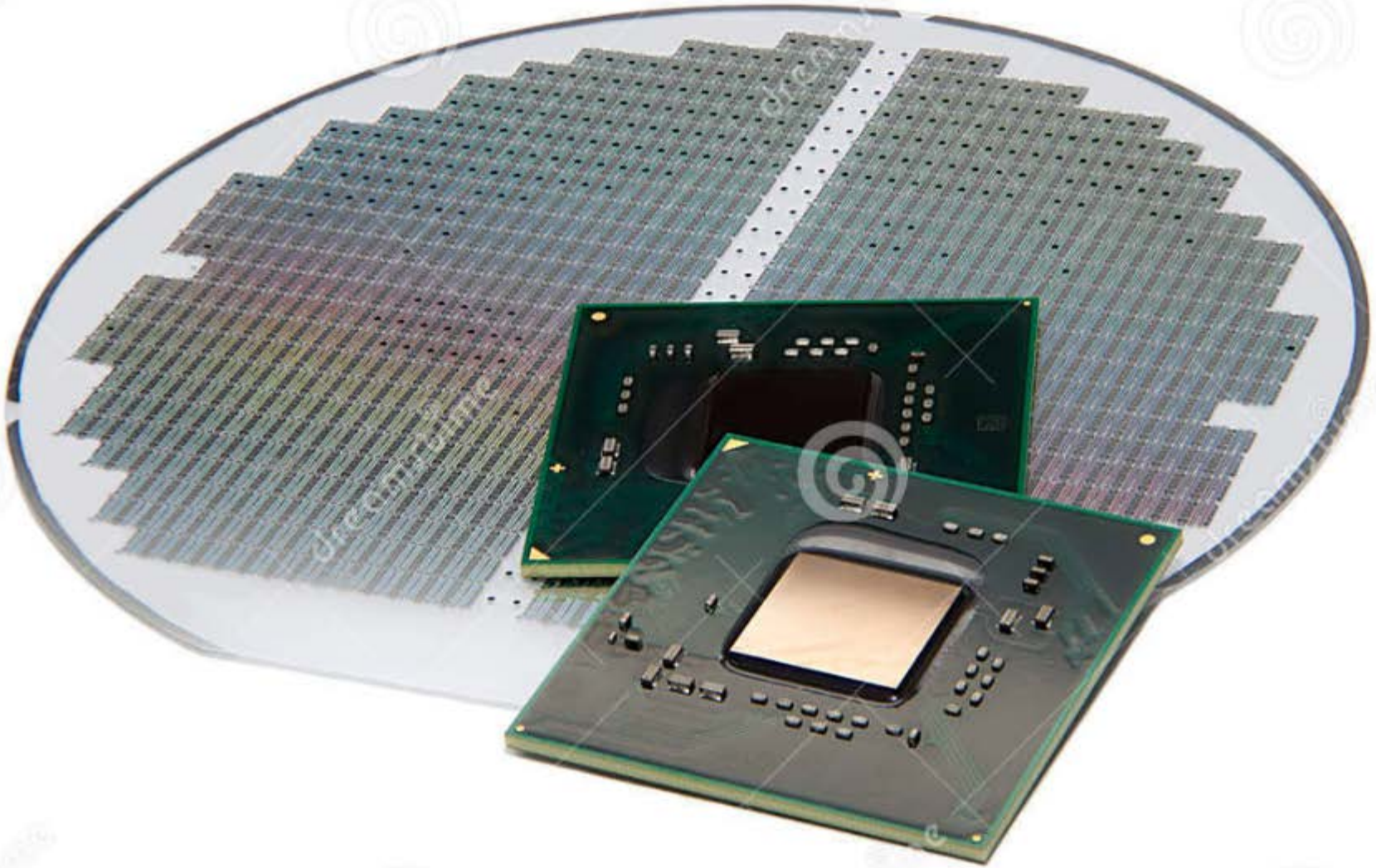



a
Al
electrode
p+
(B+ implant)
SiO2
High-purity Si
(n-Si)
300-500µm
Al
electrode
n+
(P+ implant)
b
E0
Entrance window
+U(50-100)V
U(t)
R
C
PA
MA
ADC
MCA
w
w - depletion depth


33.16
0
10
20
30



L'IMPIANTAZIONE IONICA COME STRUMENTO PER DROGARE IL SEMICONDUTTORE LOCALMENTE

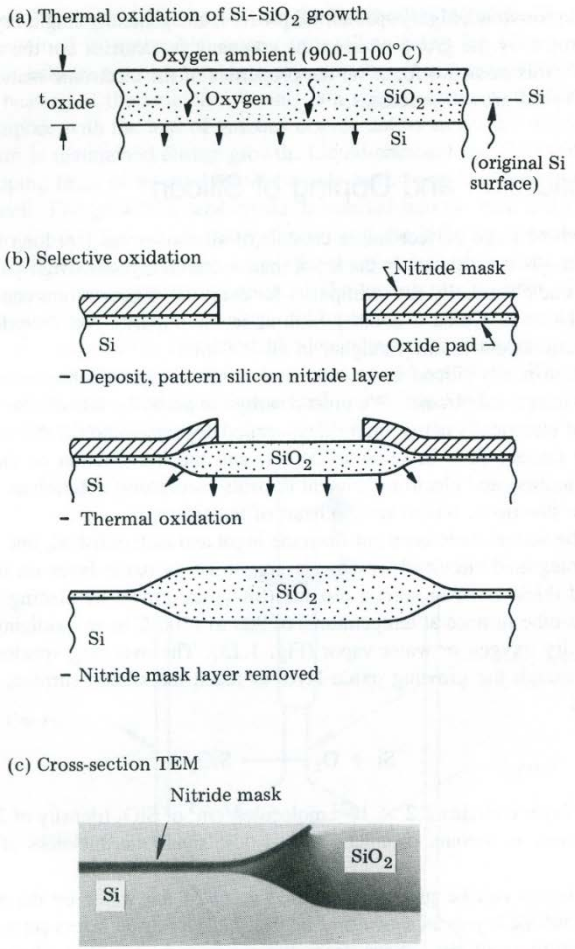
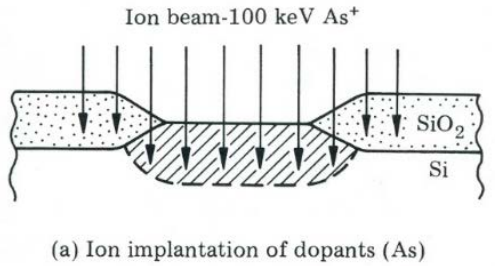
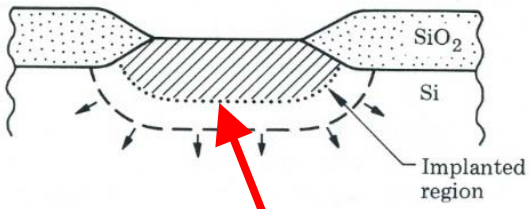


FIGURE 1.13 (a) Thermal oxidation of silicon by growth of SiO_2; (b) selective oxidation by use of nitride masks; (c) cross-sectional view of a 1.0-μm thick oxide grown with a nitride mask. [From Marcus and Sheng, (1983).]





Ion implantation of dopant (As+ or P+), and subsequent drive-in diffusion of the dopant (900-1050 °C)

MOSFET

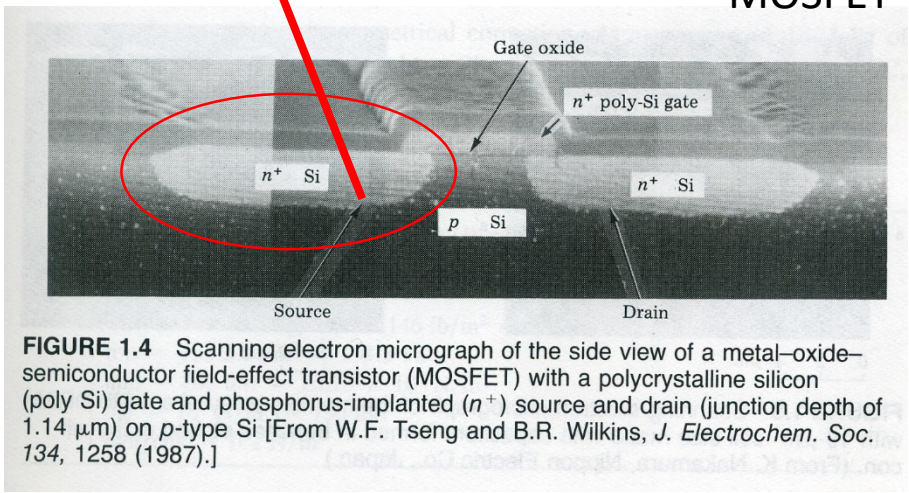
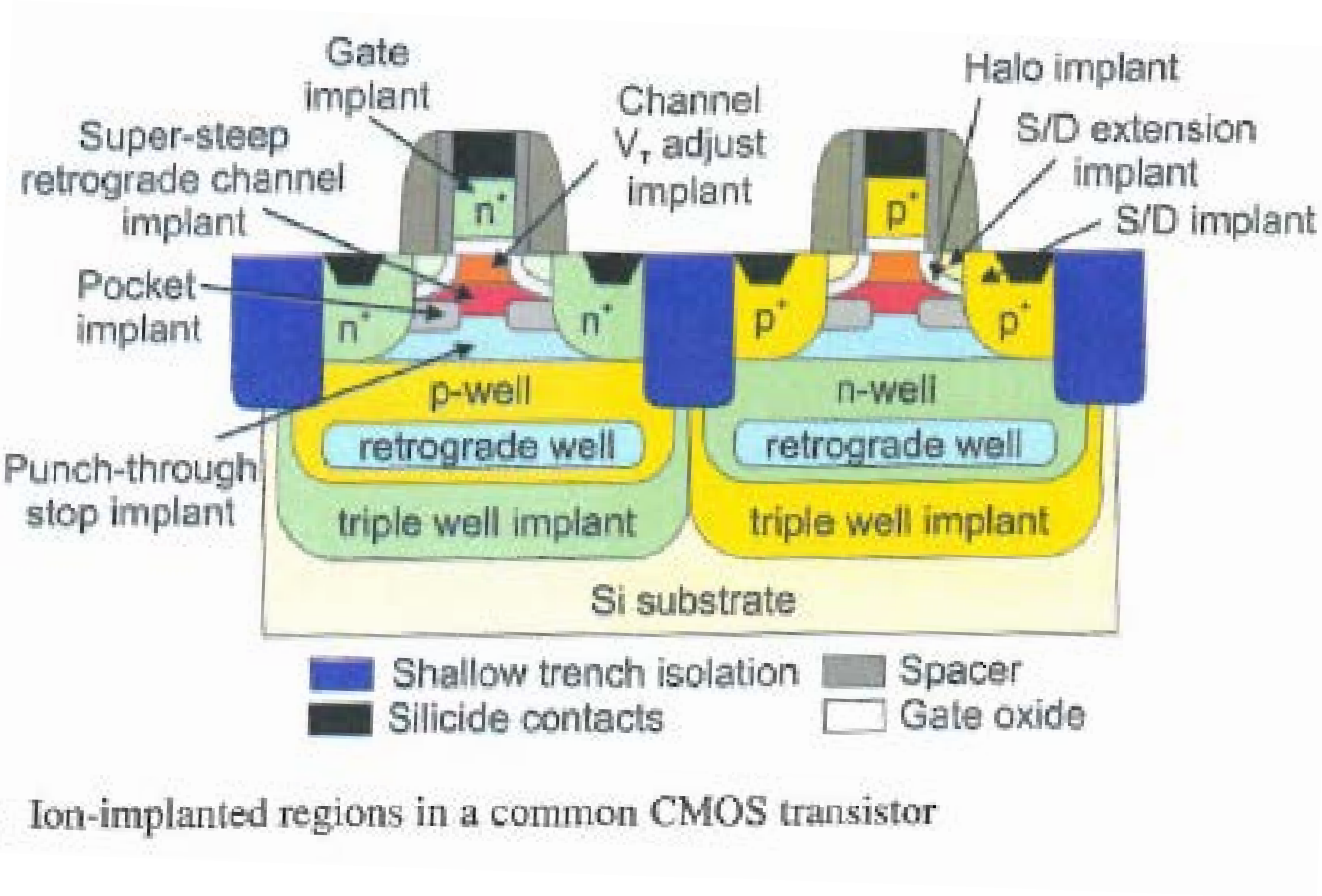


FIGURE 1.4 Scanning electron micrograph of the side view of a metal–oxide–semiconductor field-effect transistor (MOSFET) with a polycrystalline silicon (poly Si) gate and phosphorus-implanted (n^+) source and drain (junction depth of 1.14 μm) on *p*-type Si [From W.F. Tseng and B.R. Wilkins, *J. Electrochem. Soc. 134,* 1258 (1987).]



B Ion-implanted regions in a common CMOS transistor

Ion Fluence – energy of different ion implantation for silicon MOS devices and process technology

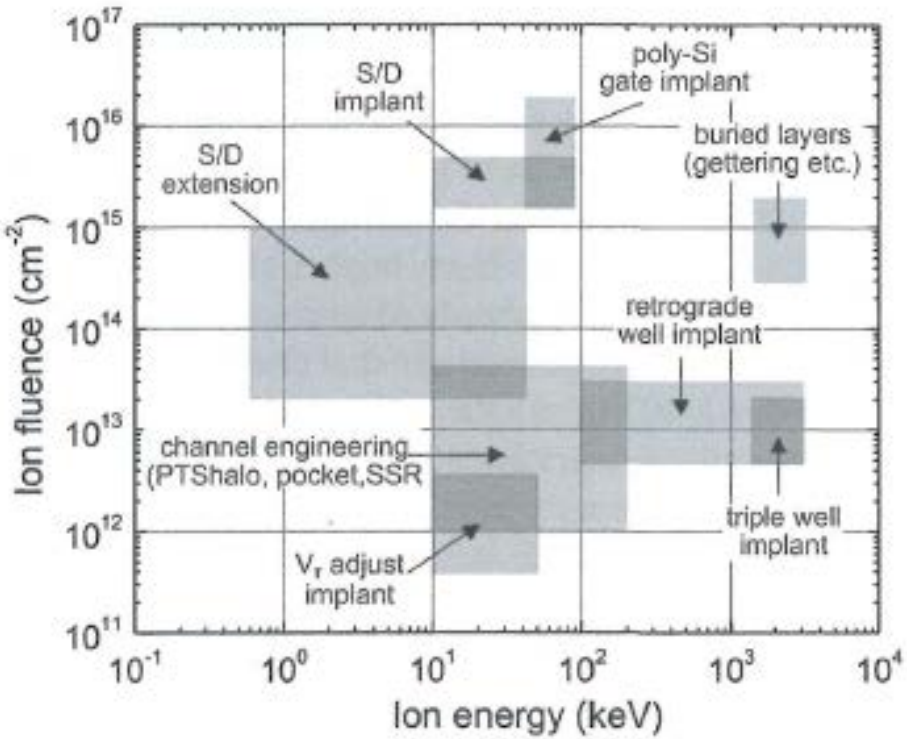


Table 4.2 Implantation processes and parameters for advanced CMOS transistor technology

Transistor region	Ions	Energy (keV)	Fluence (cm^{-2})	Remarks
Channel formation	P, B	10–80	1×10^{12}–5×10^{13}	Halo, PTS, LATIPS, Pocket, SSR
	As, In, Sb	80–200		High tilt angles and wafer re-depositioning
Transistor threshold voltage adjust	B, BF_2, As	10–50	4×10^{11}–4×10^{12} ($\rightarrow 1 \times 10^{11}$)	Transistor threshold voltage
Source/drain deep contacts	As, BF_2, B	10–80 ($\rightarrow$1–30)	2×10^{15}–8×10^{15} ($\rightarrow 1 \times 10^{15}$–$4 \times 10^{15}$)	Conducting source/drain areas
Source/drain extension	As, BF_2, B	0.5–30	3×10^{13}–1×10^{15}	Electric field reduction near S/D
poly-Si gate doping	B, BF_2, P	30–80 ($\rightarrow$2–30)	3×10^{15}–2×10^{16} ($\rightarrow 1 \times 10^{15}$–$8 \times 10^{15}$)	Conducting gate material
Preamorphization	Ge, Si	5–50	5×10^{13}–2×10^{15}	Channeling suppression
Retrograde wells	B, P	1,500–3,000	5×10^{12}–3×10^{13}	Off-state leakage current reduction
Triple wells	P, B	1,200–3,000 ($\rightarrow$5,000)	5×10^{12}–3×10^{13}	p- and n-well separation
Buried layers	B, P	1,500–3,000	2×10^{13}–5×10^{13}, 3×10^{14}–2×10^{15}	Subcollector in bipolar transistors
Proximity gettering	C, N, O, F, Si	1,500–3,000	5×10^{14}–5×10^{15}	Carrier lifetime improvement
SOI wafer fabrication	O	30–100	3×10^{16}–1×10^{17}	SIMOX
	H, He			Smart-Cut

Isbn 978-3-211-99356-9

ESEMPI CON SIMULAZIONI TRIM

- Si può ottenere un drogaggio selettivo di un semiconduttore con controllo sulla profondità sulla scala di 10-100nm mediante acceleratori di ioni con energie da 10keV a 500keV
- Il controllo sulla posizione è demandato alle maschere ottenute con tecniche di foto-litografia e deposizione di film sottili.

- Si può modificare il materiale in profondità dell‘ordine delle decine di micrometri con ioni leggeri dell’energia di qualche MeV

Proton beam writing

Proton beam (p-beam) writing is a new direct-writing process that uses a focused beam of MeV protons to pattern resist material at nanodimensions. The process, although similar in many ways to direct writing using electrons, nevertheless offers some interesting and unique advantages. Protons, being more massive, have deeper penetration in materials while maintaining a straight path, enabling p-beam writing to fabricate three-dimensional, high aspect ratio structures with vertical, smooth sidewalls and low line-edge roughness. Calculations have also indicated that p-beam writing exhibits minimal proximity effects, since the secondary electrons induced in proton/electron collisions have low energy. A further advantage stems from the ability of protons to displace atoms while traversing material, thereby increasing localized damage especially at the end of range. P-beam writing produces resistive patterns at depth in Si, allowing patterning of selective regions with different optical properties as well as the removal of undamaged regions via electrochemical etching.

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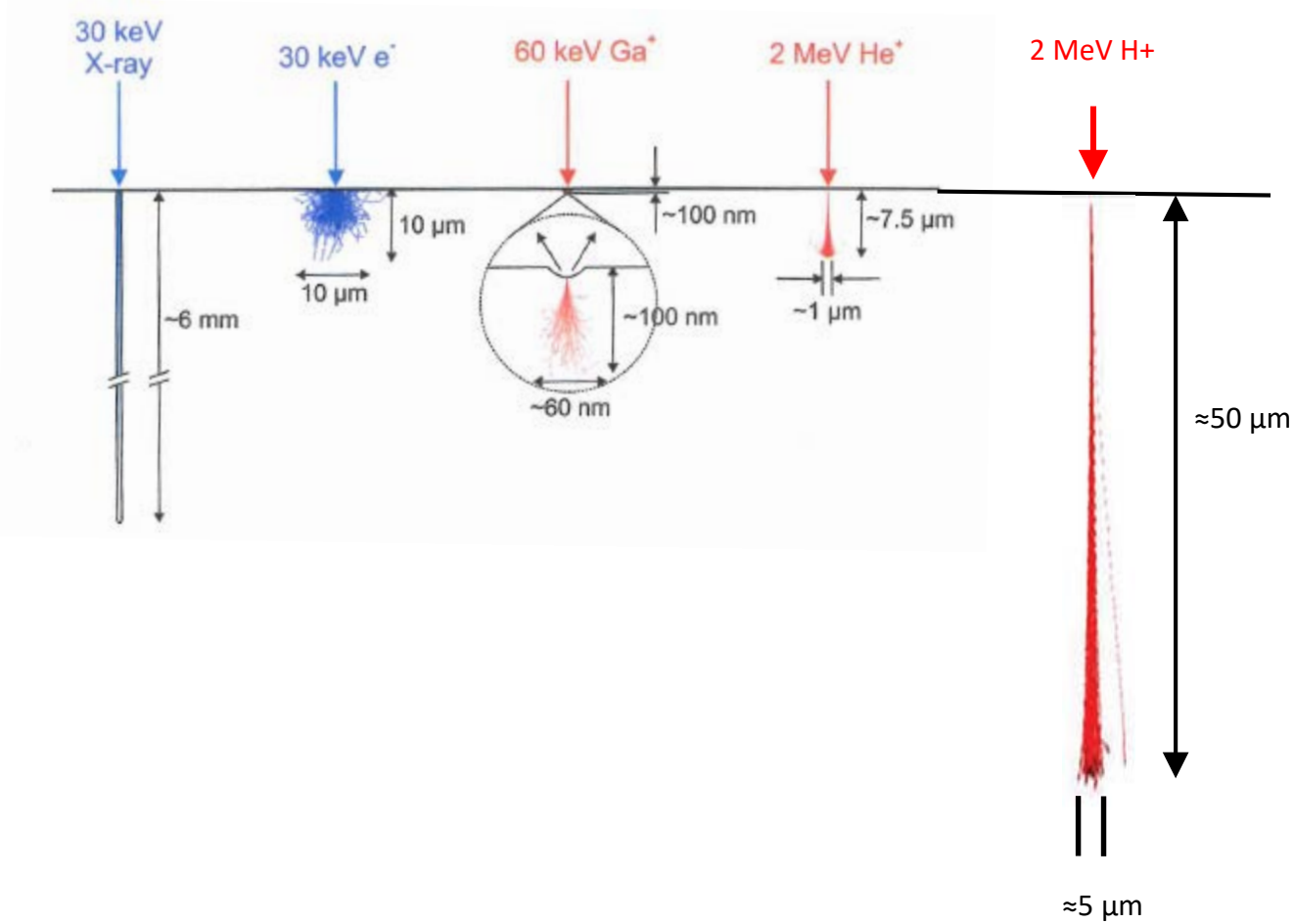
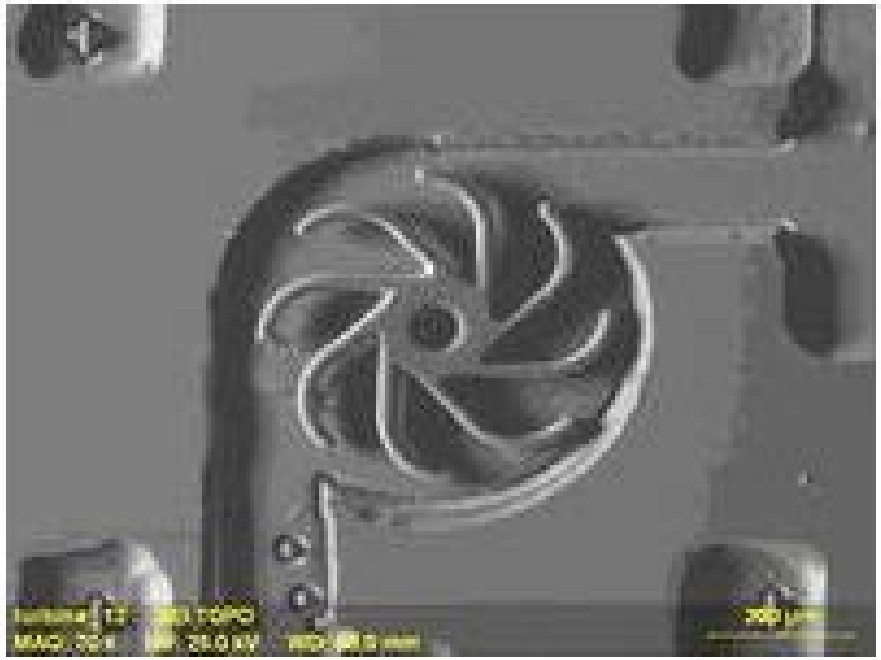
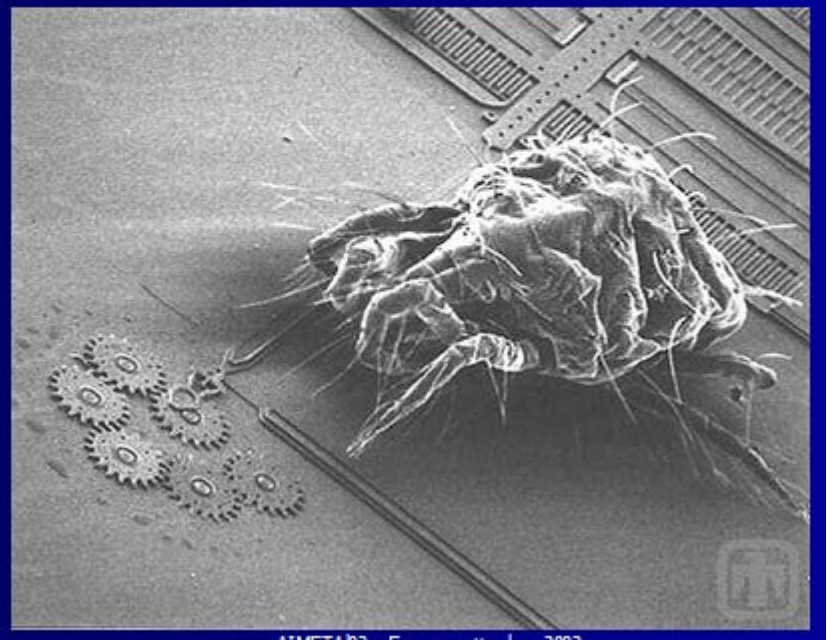
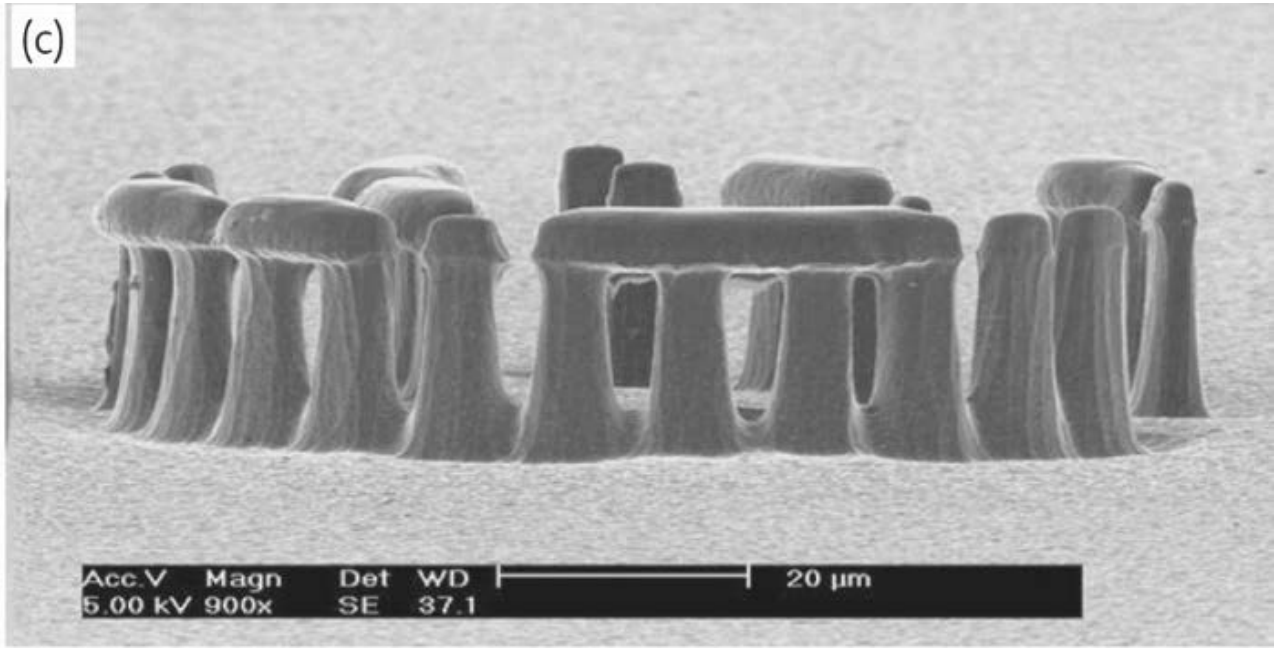
Centre for Ion Beam Applications (CIBA), Physics Department, National University of Singapore, Singapore 117542
*E-mail: phywattf@nus.edu.sg

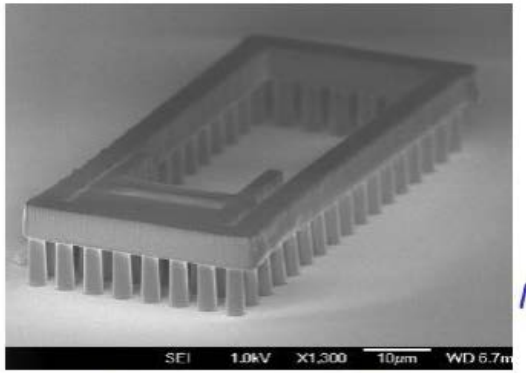




Micromacchine: *componenti*

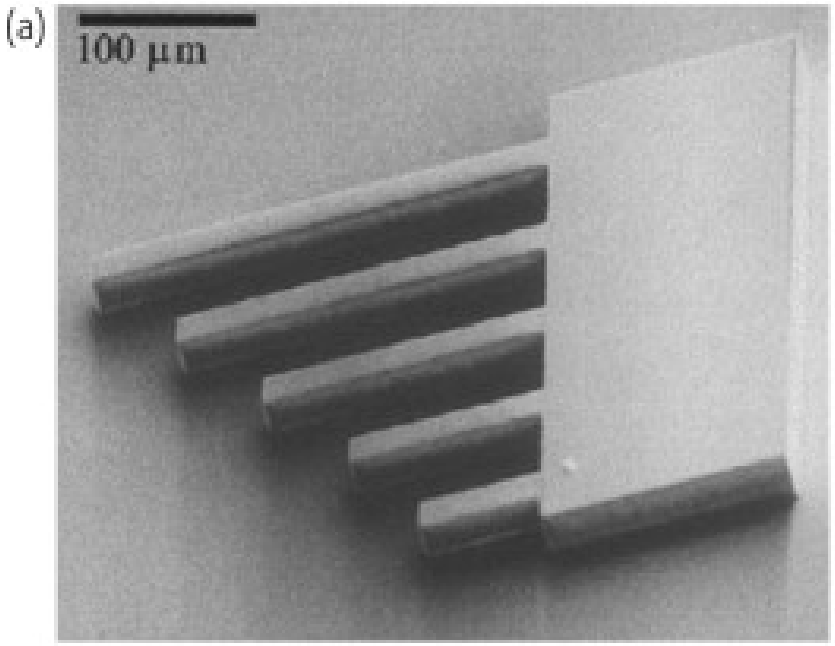


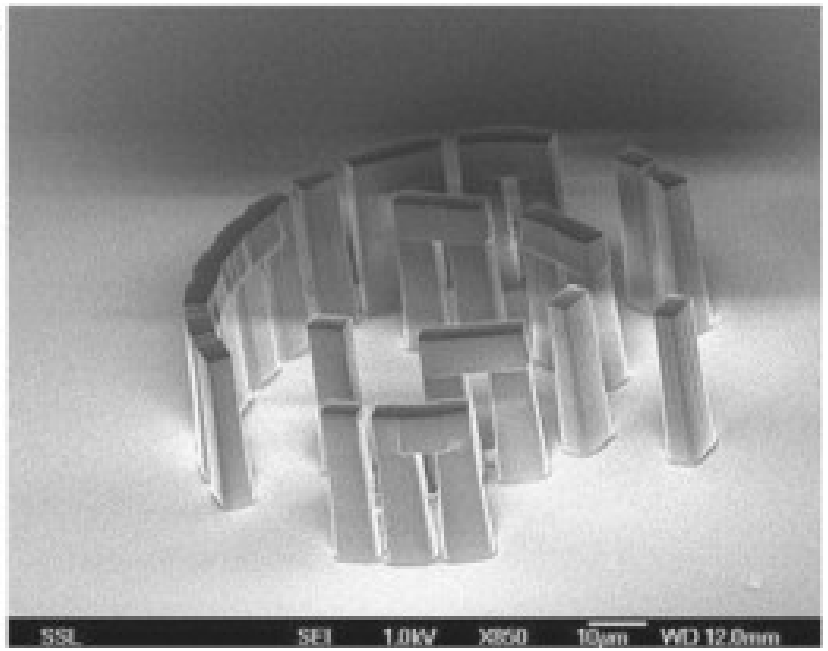


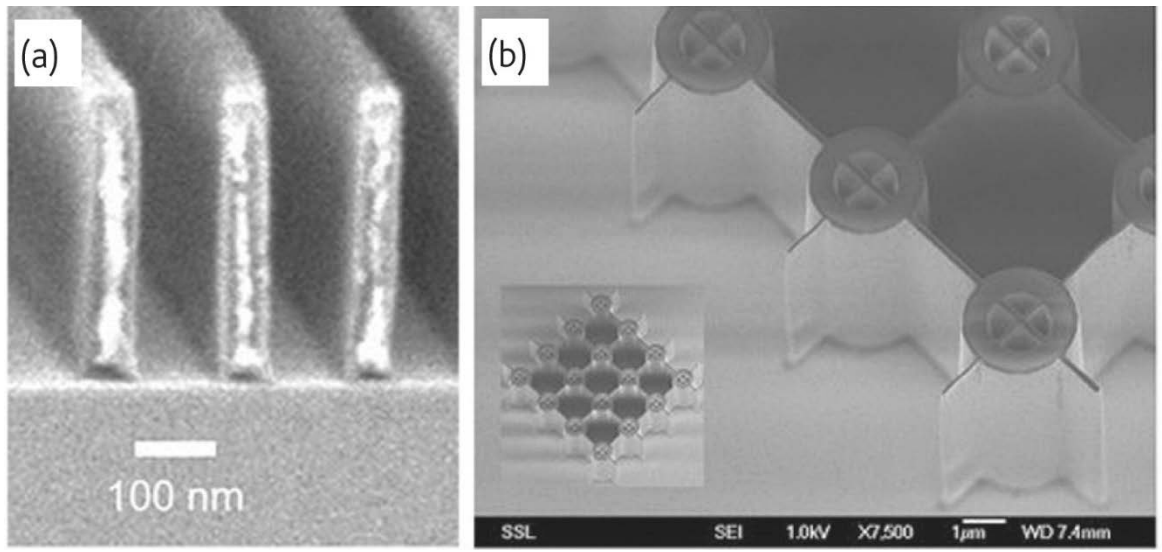


Parthenon's copy with a reduction of 1 million times

J. A. van Kan, P. G. Shao, K. Ansari, A. A. Bettiol, T. Osipowicz, F. Watt, Microsyst Technol 13 431(2007



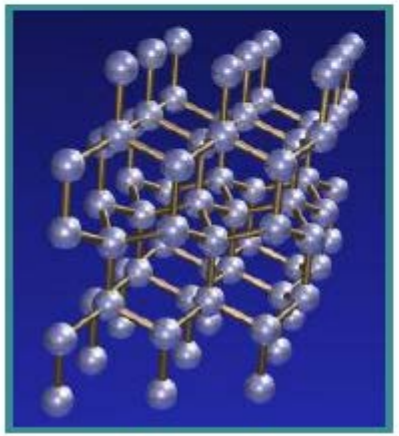




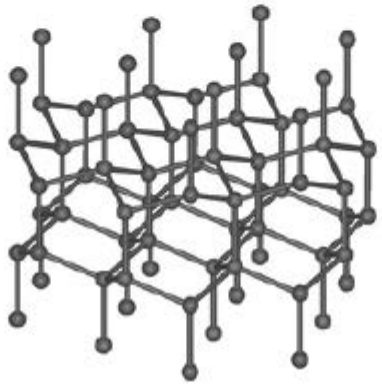
https://www.sciencedirect.com/science/article/pii/S1369702107701293#fig1

Diamond

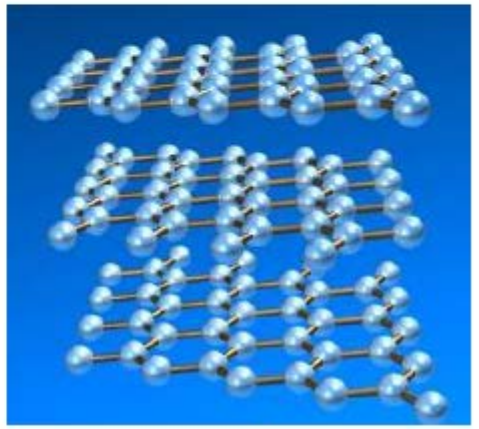
αδάμας (*indestructible*)



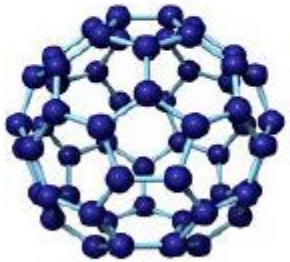
diamond



londsaelite

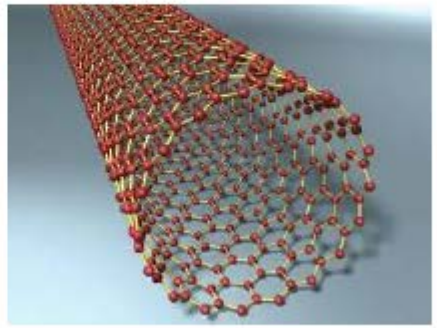


graphite

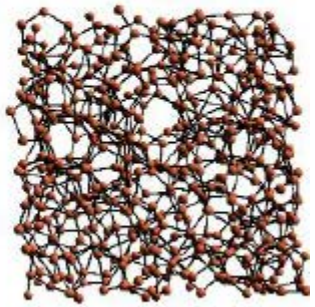


fullerene

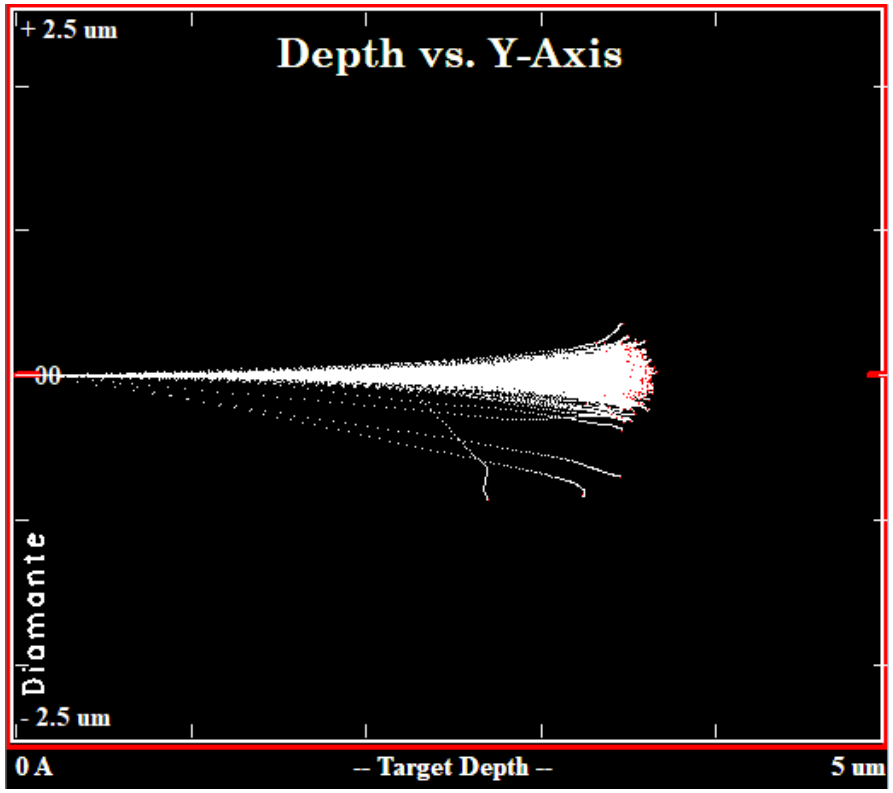
graphene



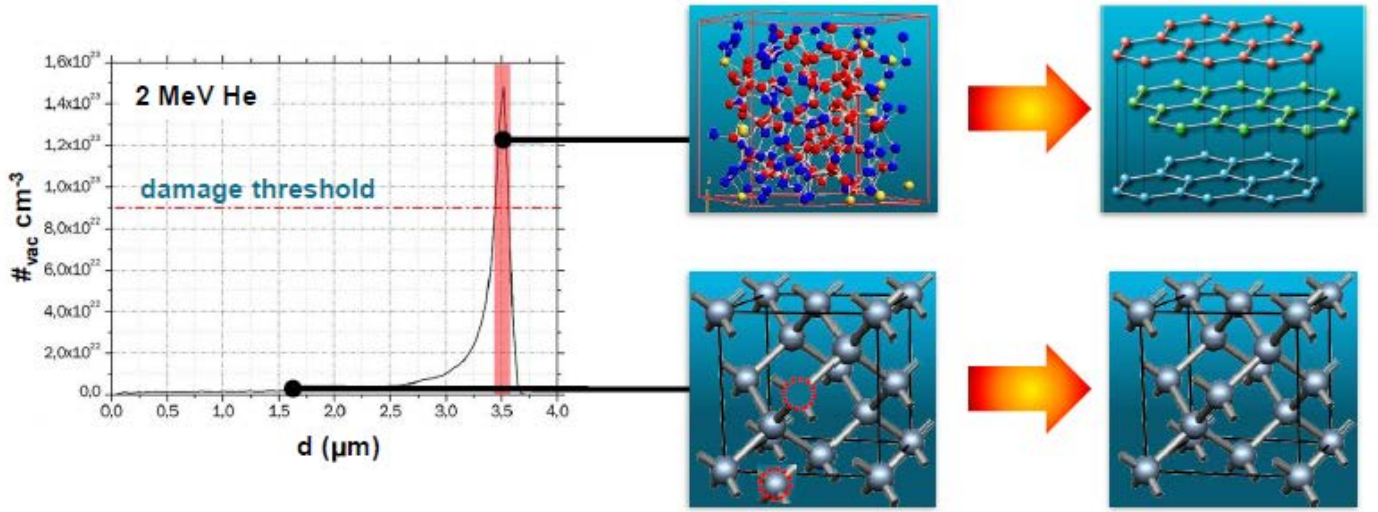
nanotube



amorphous carbon



Thermal annealing



- Above threshold: amorphous carbon → polycrystalline graphite
- Below threshold: diamond with Frenkel defects → diamond

The diamond lift-off technique

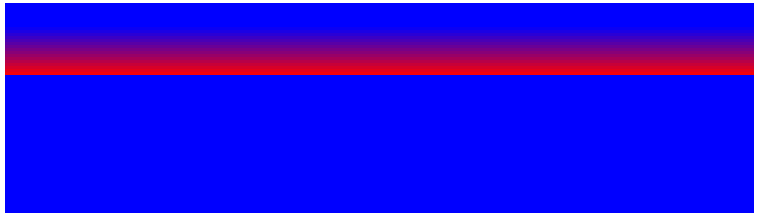
Single-crystal diamond plate liftoff achieved by ion implantation and subsequent annealing

N. R. Parikh, J. D. Hunn, E. McGucken, and M. L. Swanson
University of North Carolina, Chapel Hill, North Carolina 27599-3255

C. W. White
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831-6048

R. A. Rudder, D. P. Malta, J. B. Posthill, and R. J. Markunas
Research Triangle Institute, Research Triangle Park, North Carolina 27709-2194

Appl. Phys. Lett. 61 (25), 28 December 1992 3124



- **MeV ion implantation**

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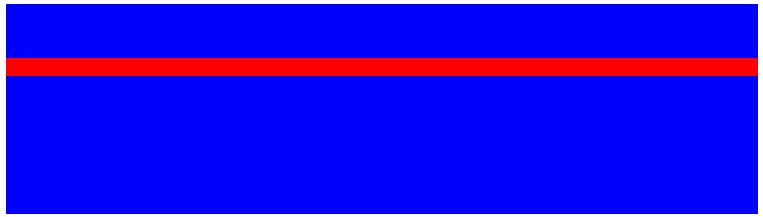

- **MeV ion implantation**
- **Thermal annealing**

The diamond lift-off technique

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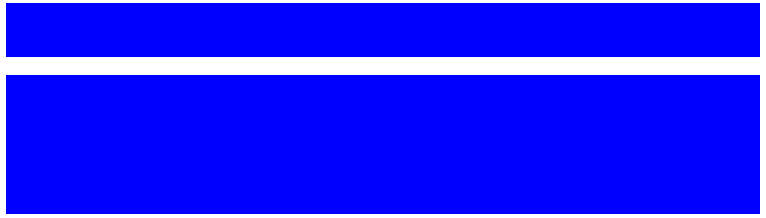

- **MeV ion implantation**
- **Thermal annealing**
- **Selective graphite etching**

The diamond lift-off technique

Single-crystal diamond plate liftoff achieved by ion implantation and subsequent annealing

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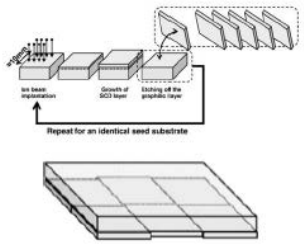
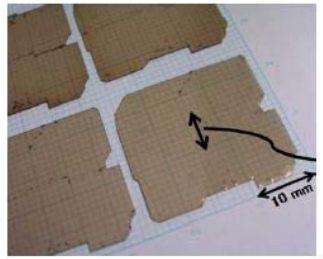
Lift-off + CVD growth

Developments of elemental technologies to produce inch-size single-crystal diamond wafers

Hideaki Yamada *, Akiyoshi Chayahara, Yoshiaki Mokuno, Nobuteru Tsubouchi, Shin-ichi Shikata, Naoji Fujimori





- MeV ion implantation
- Thermal annealing
- Selective graphite etching
- Lift-out

Lift-off + laser micro-cutting

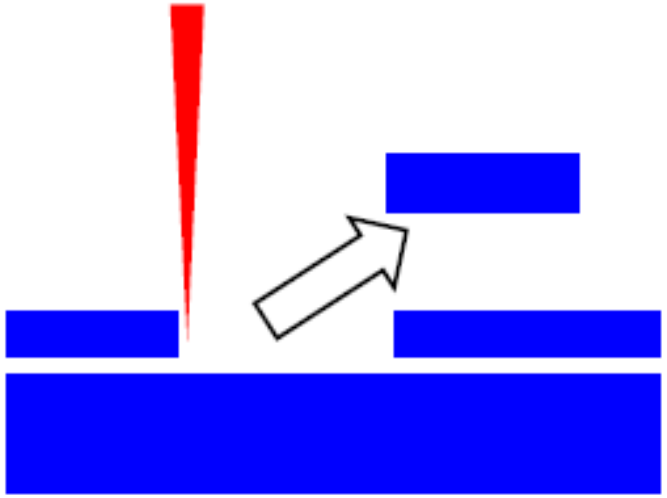
Fabrication of single-crystal diamond microcomponents

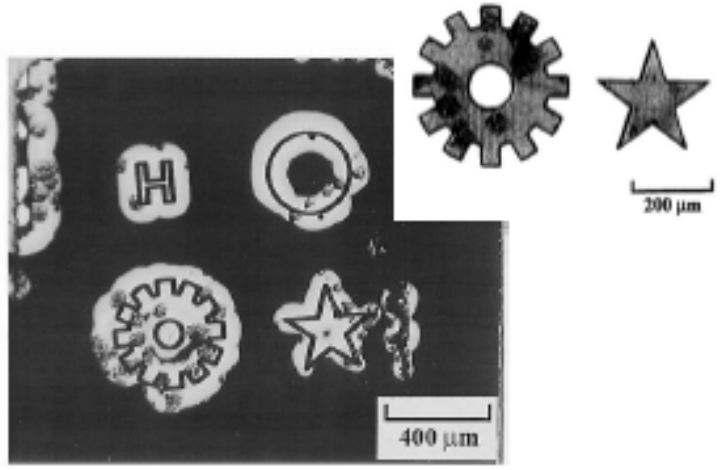
John D. Hunn, S. P. Withrow, C. W. White, R. E. Clausing, and L. Heatherly
Oak Ridge National Laboratory, Bldg 5500 MS-6376, Oak Ridge, Tennessee 37831-6376

C. Paul Christensen
Potomac Photonics, Lanham, Maryland 20706

(Received 26 August 1994; accepted for publication 7 October 1994)

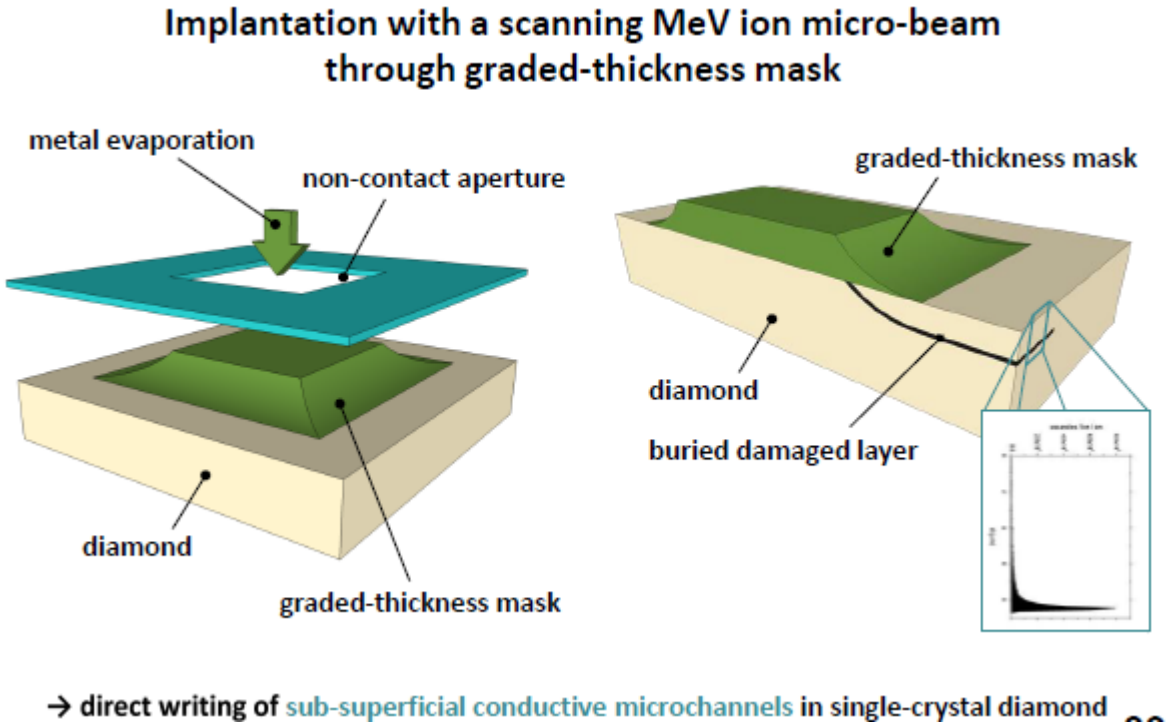
We have combined a technique for the lift-off of thin diamond films from a bulk diamond with a technique for engraving diamond with a focused excimer laser to produce free-standing single-crystal diamond microstructures. One microcomponent that has been produced is a 12 tooth gear ~400 μm in diameter and ~13 μm thick. Other microstructures have also been demonstrated, showing the versatility of this method. This process should be applicable to producing diamond microcomponents down to spatial dimensions (width and thickness) of a few micrometers. © *1994 American Institute of Physics.*

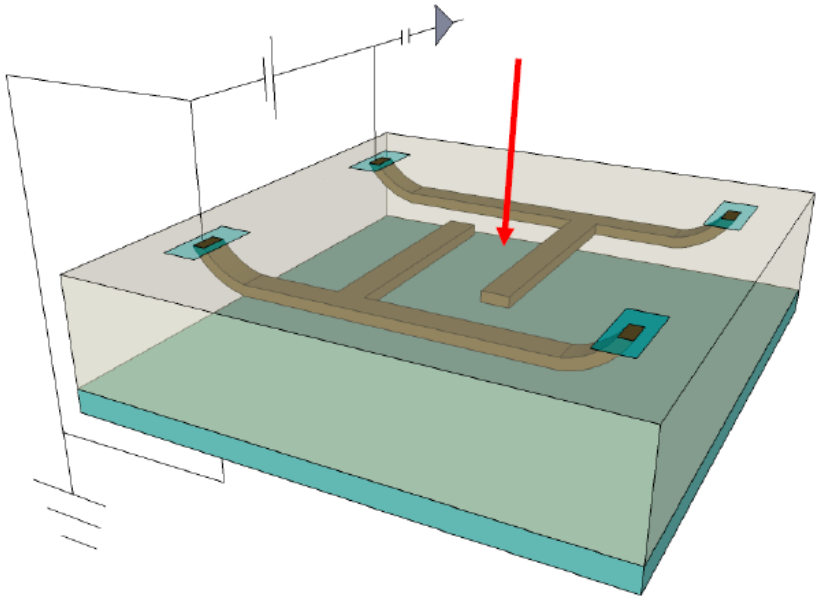




MICRO CONTATTI

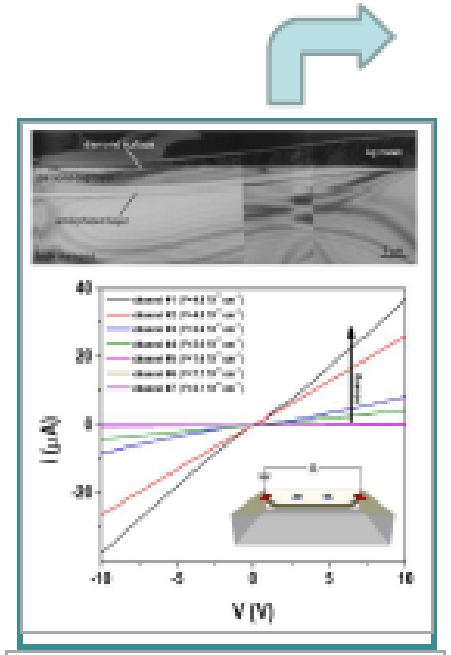
- RIVELATORI DI RADIAZIONE SENSIBILI ALLA POSIZIONE
- MICRO-SENSORI BIOLOGICI



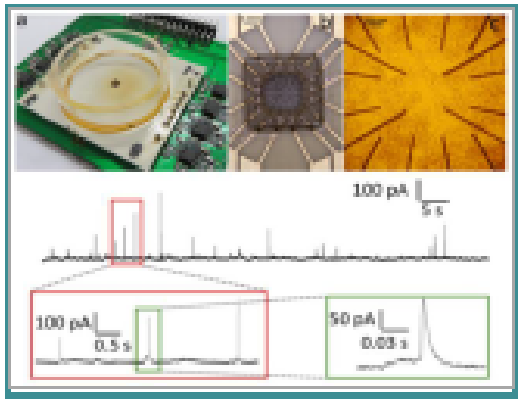


SENSORI E RIVELATORI A DIAMANTE

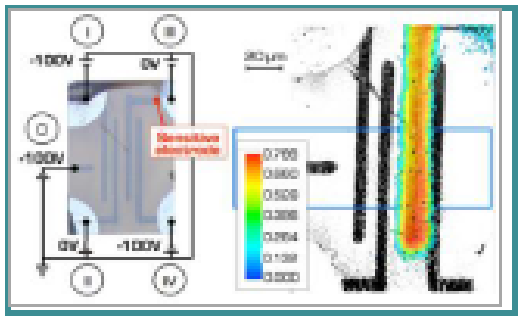
Development of artificial diamond devices for the simultaneous detection of cell signals and ionizing radiation for applications in micro-radiobiology



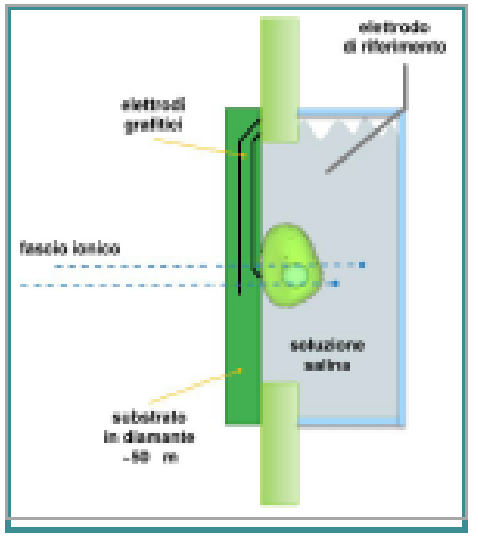
Deep ion beam lithography



Cellular bio-sensors



Radiation detectors



Integrated device

DIAMANTE AMORFO ?

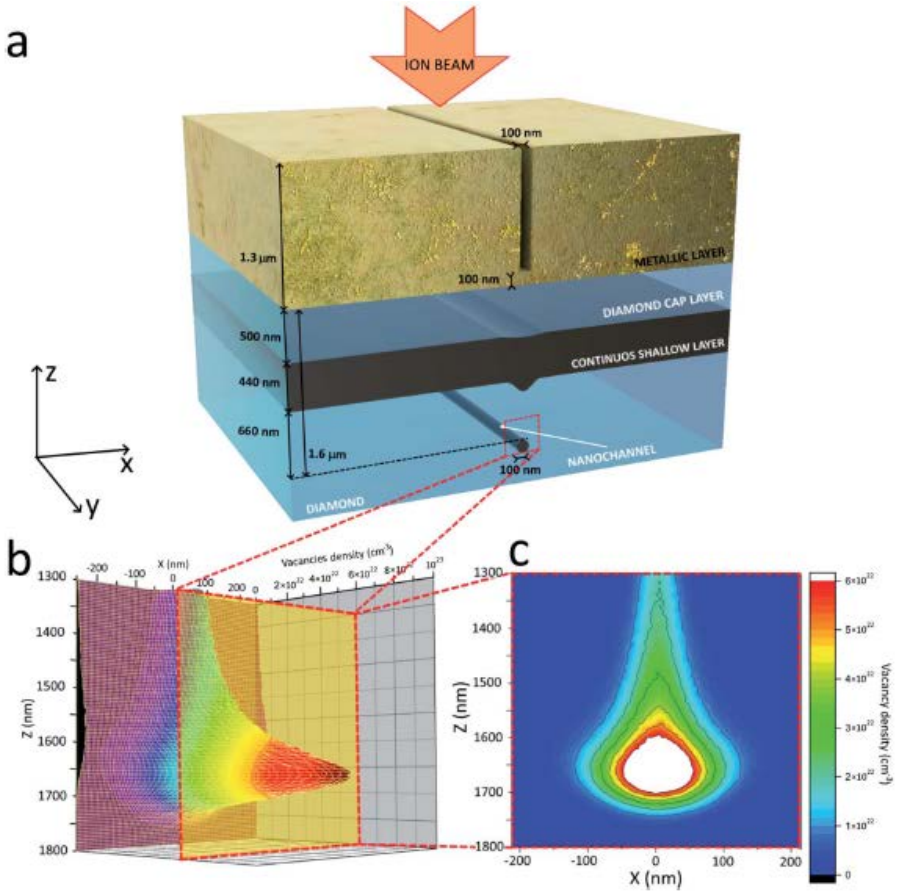
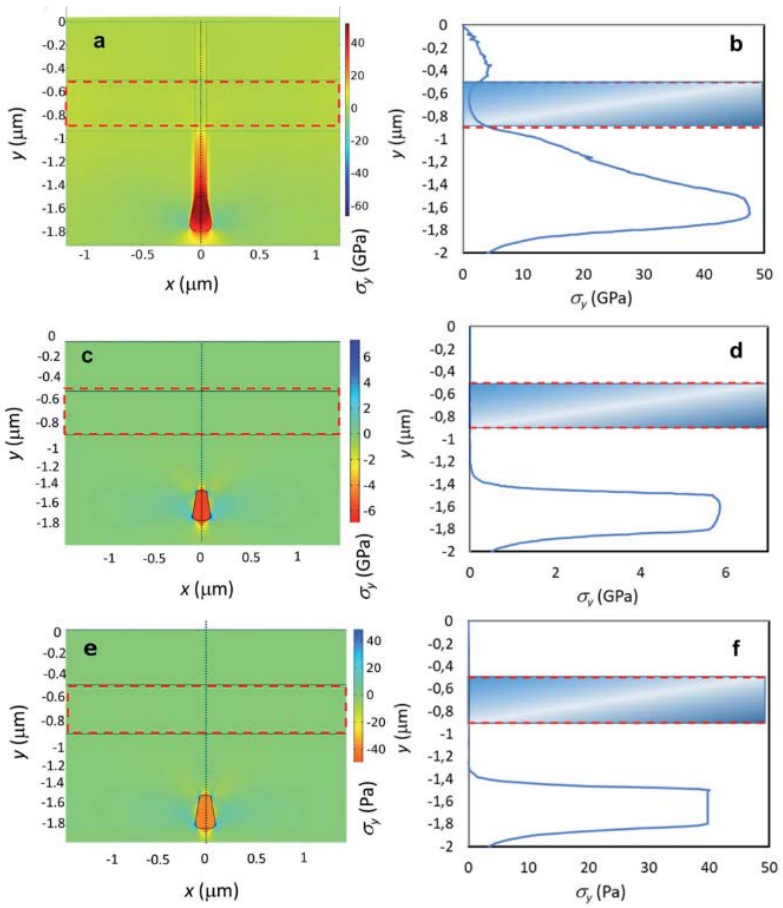
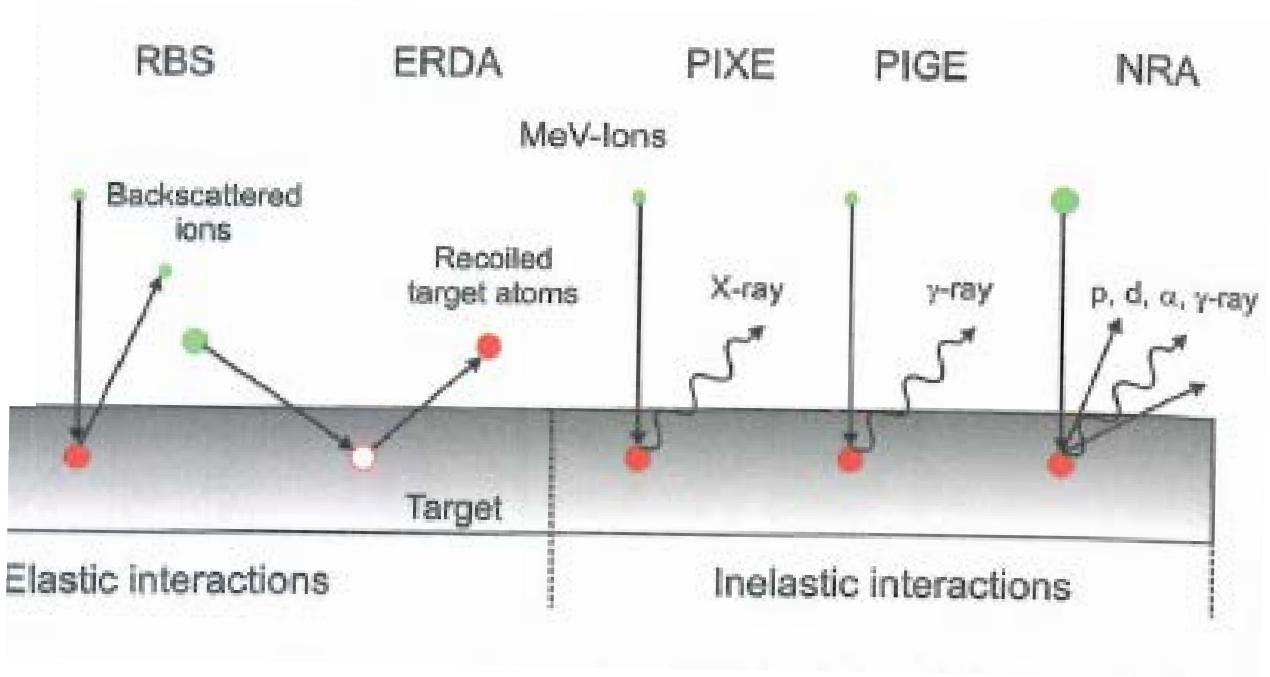


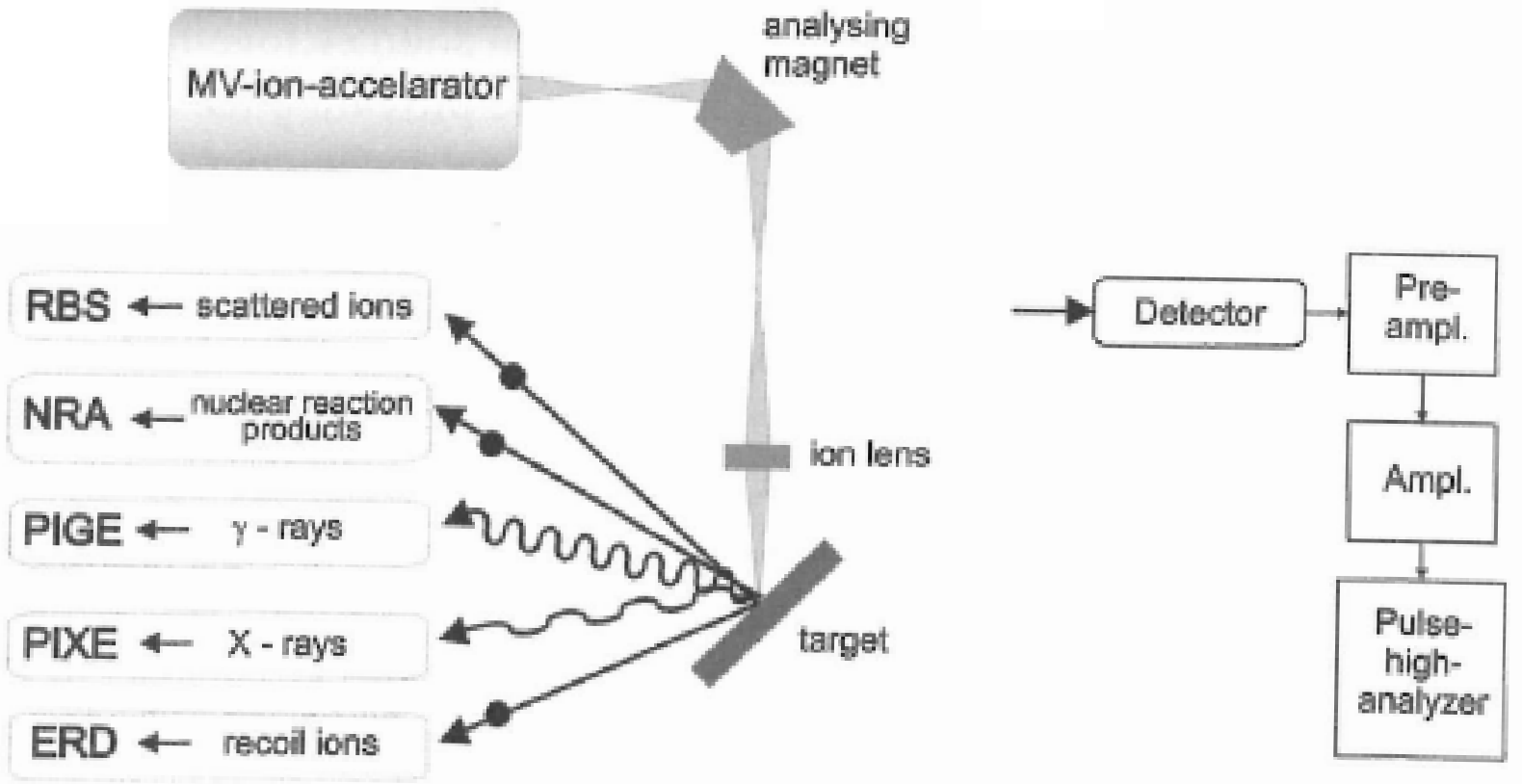
Fig. 1 Sample geometry and profile of the ion-induced structural damage. (a) Schematic representation of the sample geometry: the metallic mask with the nanometric aperture determines the formation of both the continuous shallow layer and of the nanochannel upon MeV ion irradiation. (b) Three-dimensional plot of the cross-sectional profile of ion-induced damage density as resulting from SRIM simulation. (c) Corresponding two-dimensional plot: the size and shape of the region damaged beyond the estimated critical threshold (in red) corresponds to the features observed in Fig. 4a; note that the same plot is reported as an inset of Fig. 4a for sake of comparison with experimental data.



Nanoscale Advances, 2021, DOI: 10.1039/D1NA00136A

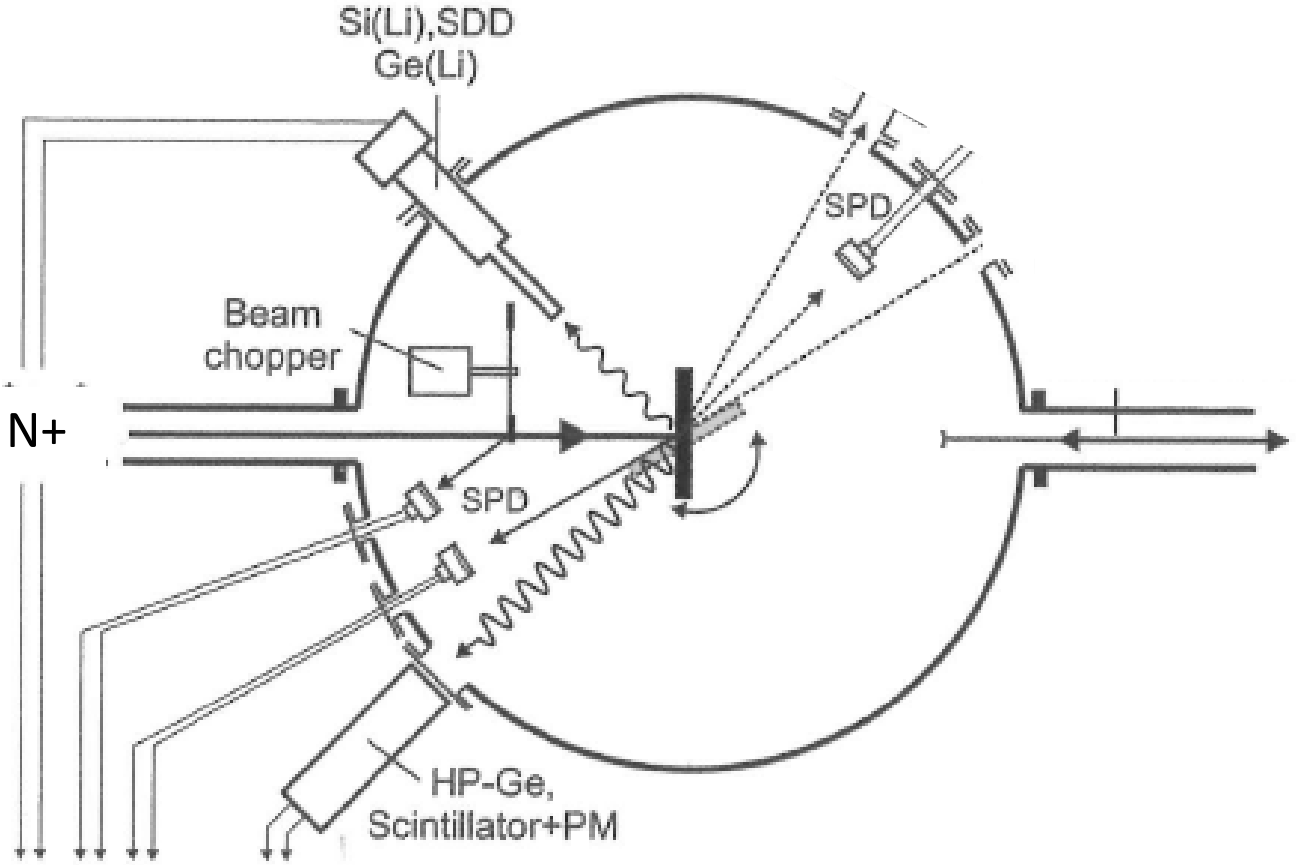
ACCELERATORI DI IONI PER ANALISI DEI MATERIALI





Schematic overview of accelerator-based IBA techniques (a) and radiation detection system arrangement (b) for particle and photon radiations emitted from a target surface during ion–solid interaction

ION BEAM H+, He+, N+



Experimental setup for combined IBA techniques (schematically, after [9, 10])

Sir Ernest Rutherford (1871 - 1937)

- 1911: Rutherford's scattering experiments: ^{4}He on Au

  $\Rightarrow$ Atomic nucleus, nature of the atom

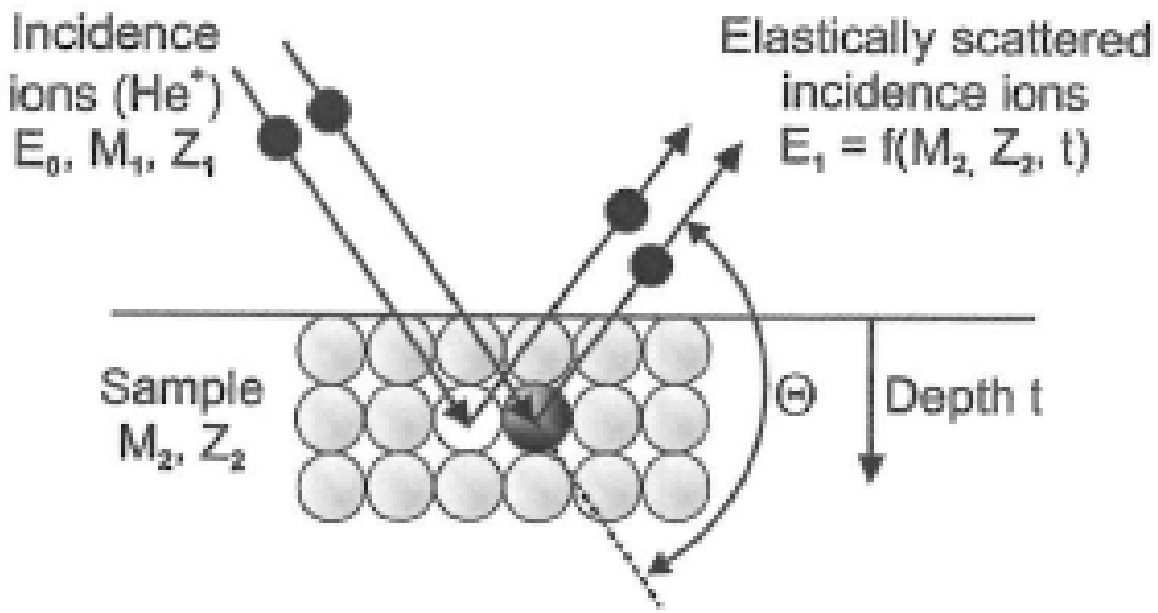
RBS as materials analysis method

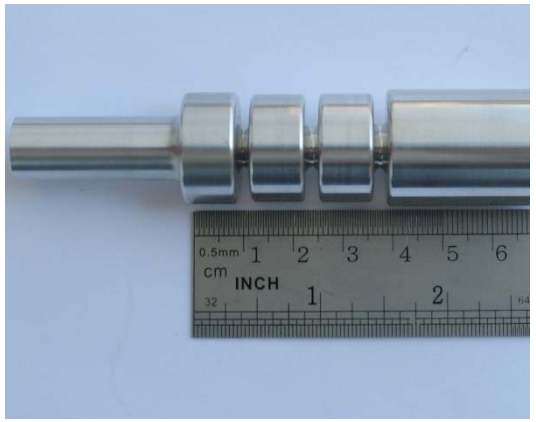
- 1957: S. Rubin, T.O. Passell, E. Bailey, "Chemical Analysis of Surfaces by Nuclear Methods", *Analytical Chemistry* 29 (1957) 736

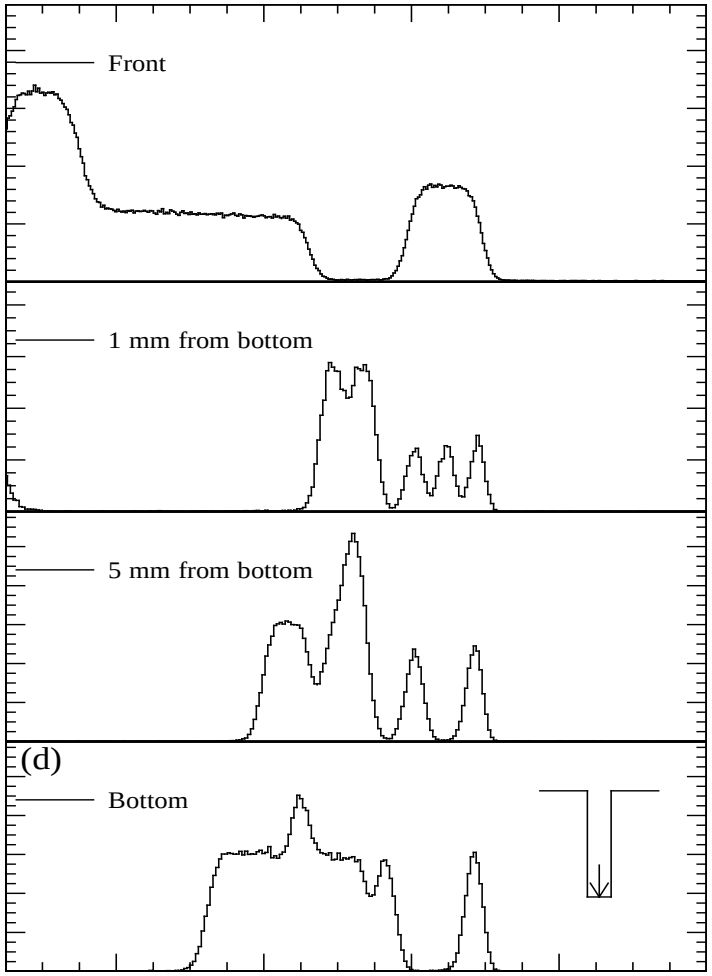
"Nuclear scattering and nuclear reactions induced by high energy protons and deuterons have been applied to the analysis of solid surfaces. The theory of the scattering method, and determination of O, Al, Si, S, Ca, Fe, Cu, Ag, Ba, and Pb by scattering method are described. C, N, O, F, and Na were also determined by nuclear reactions other than scattering. The methods are applicable to the detection of all elements to a depth of several μm, with sensitivities in the range of 10^{-8} to 10^{-6} g/cm^2."

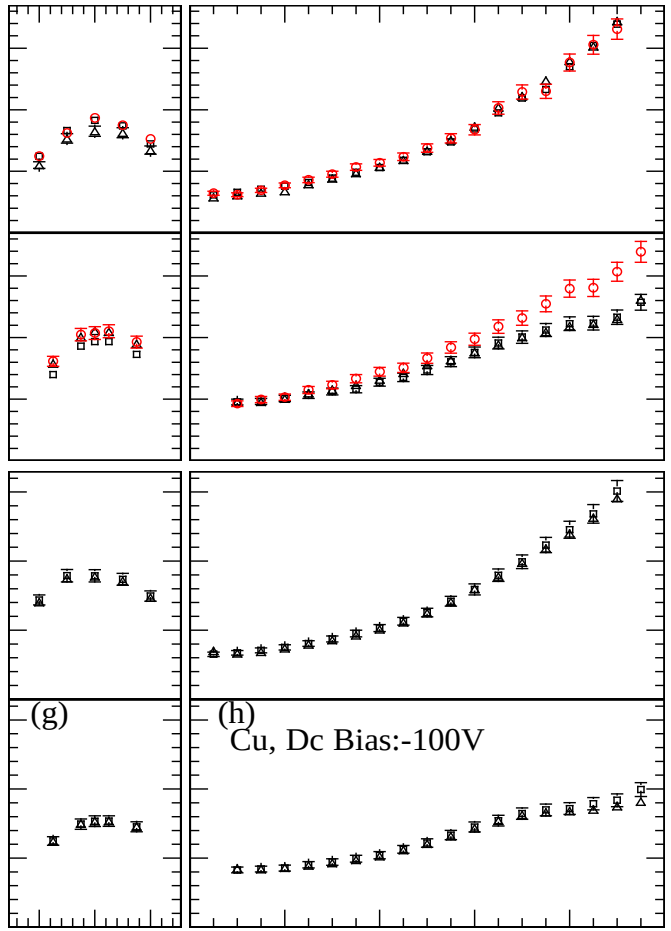
RBS

Physical principle of Rutherford backscattering (schematically)



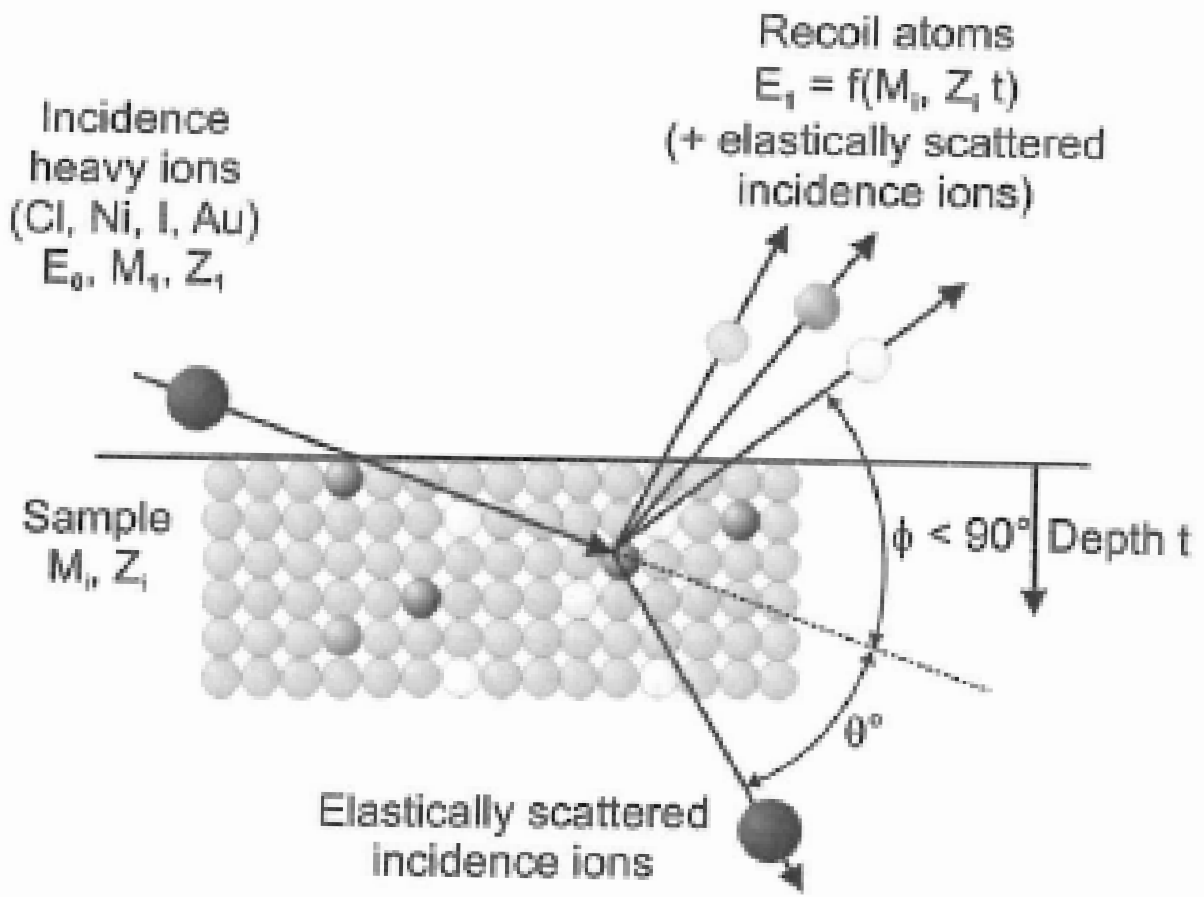

0.5mm
cm
INCH


Front
1 mm from bottom
5 mm from bottom
(d)
Bottom

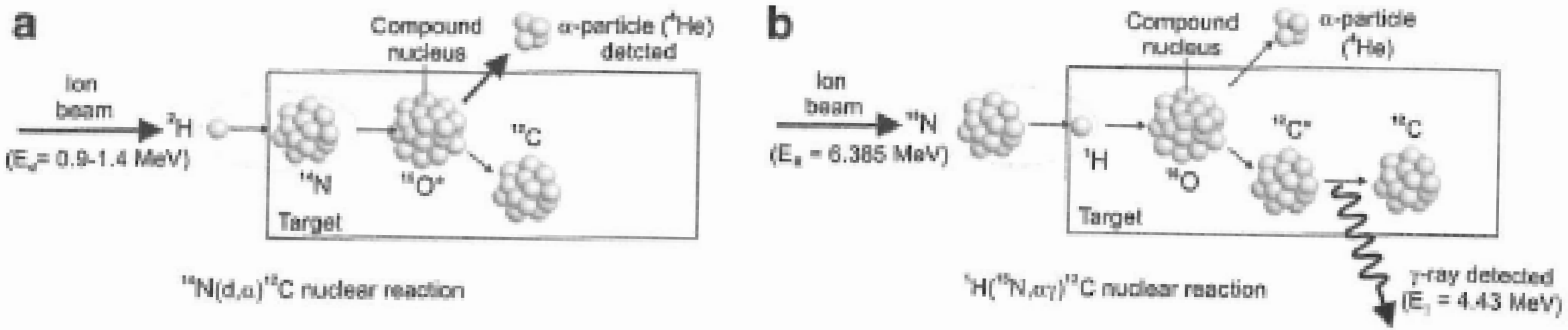

(g)
(h)
Cu, Dc Bias:-100V

ERD

Physical principle of elastic recoil detection analysis (ERDA) with θ the scattering angle and ϕ the recoil angle which is actually the detector angle



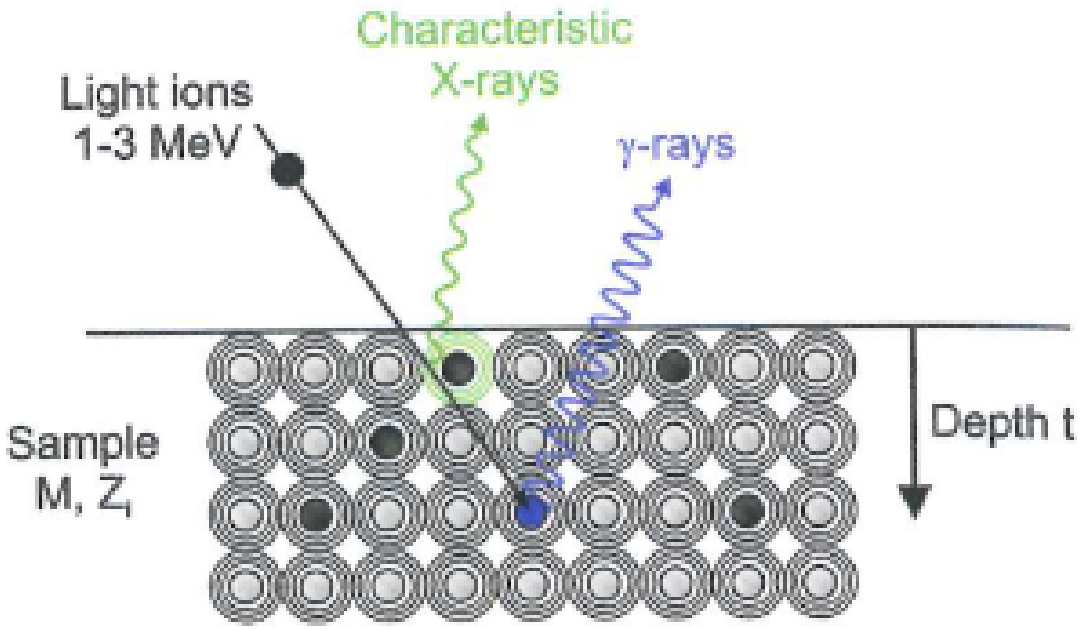
NRA



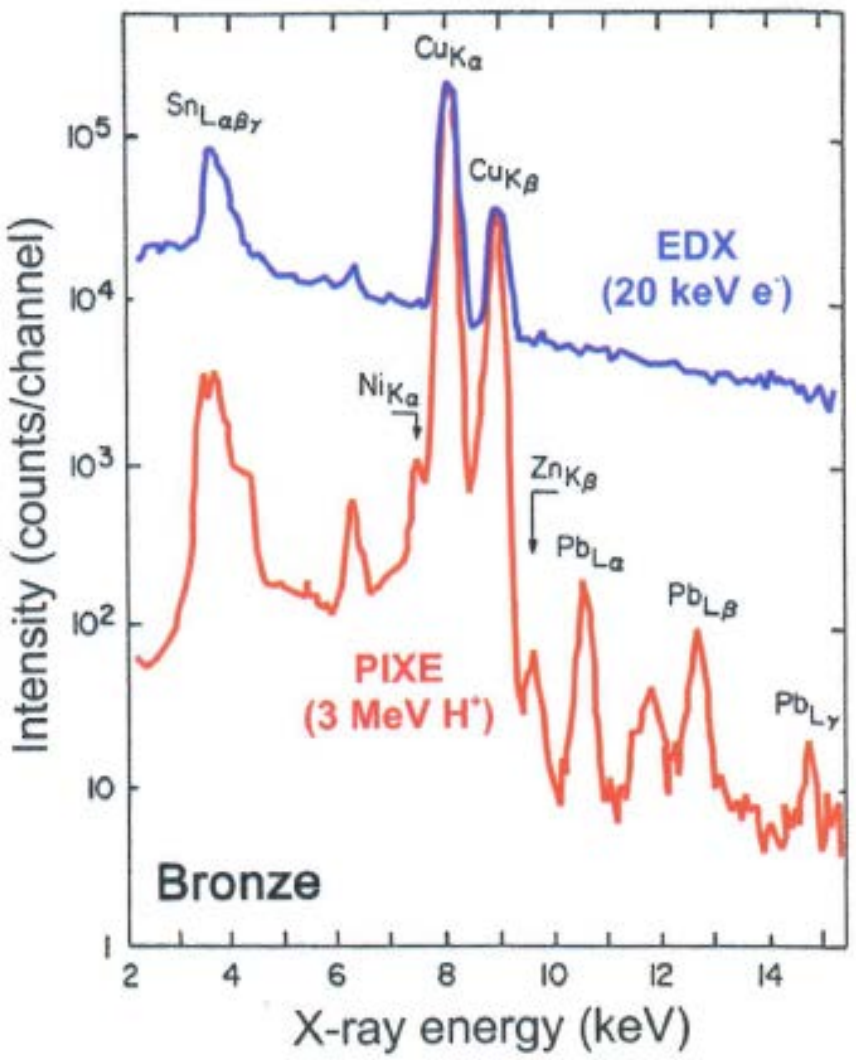
Physical principle of nuclear reaction analysis (NRA) for two typical reactions: (a) $^{14}N(d,\alpha)^{12}C$ nuclear reaction with detection of the emitted α-particle for depth profiling of nitrogen, and (**b**) $^{1}H(^{15}N,\alpha\gamma)^{12}C$ nuclear reaction with the detection of the emitted γ-ray for depth profiling of hydrogen

PIXE, PIGE

Physical scheme of ion induced photon emission from atomic electron shells (X-ray) or atomic nuclei (γ-ray)



Comparison of PIXE (*red line*) and EDX (*blue line*) spectra taken from a bronze sample. PIXE is generally about 100 times more element sensitive [4]



E QUESTO E’ SOLO UN ASSAGGIO DELLE POTENZIALITA’ OFFERTE DALL’IMPIEGO DI IONI ACCELERATI NELLA SCIENZA E TECNOLOGIA

Grazie per l’attenzione