Semiconductor Devices - 2014

Lecture Course
Part of
SS Module PY4P03

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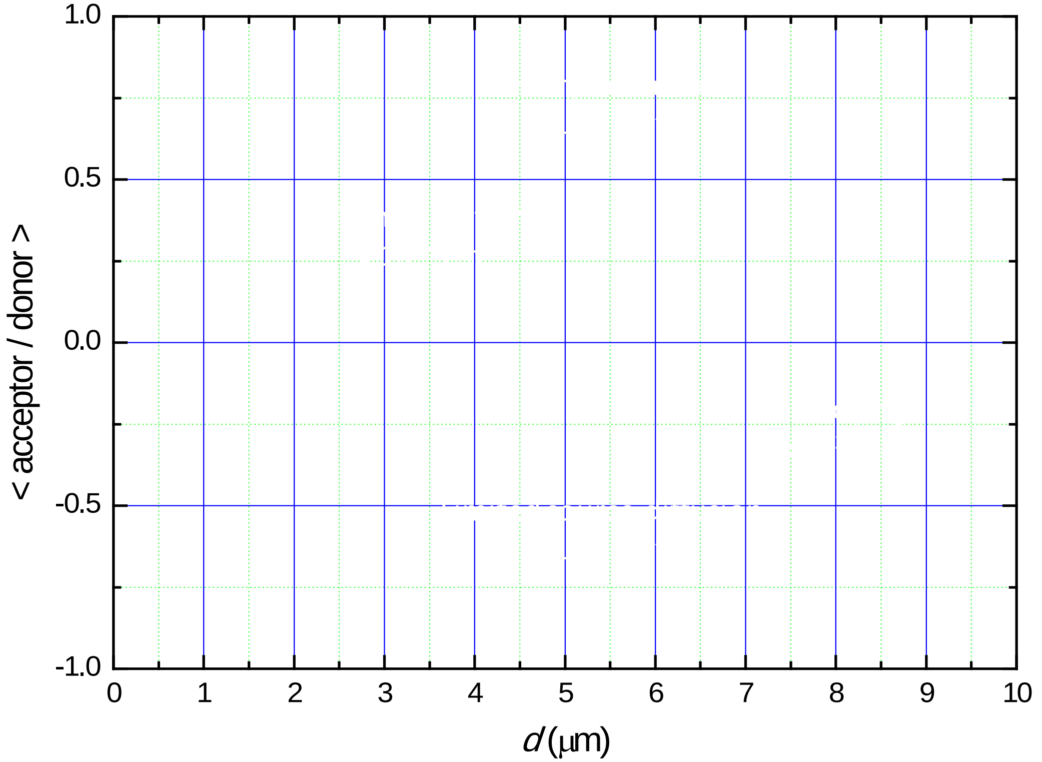
MAGNETISM & SPINTRONICS
Trinity College Dublin

Doping Techniques

- Alloying
- Diffusion
- Ion Implantation
- Transmutation

- Density
- Profile
- Complexity
- Cost



Alloying

- Alloying is a rather conventional method for device preparation, presently used mainly for medium and high-power bipolar devices.
- It involves the mechanical assembly of structures from p- and n-type semiconductor and heat-treatment in a protective atmosphere, allowing for the formation of metallurgical alloyed junctions.
- It was the first method used for the large-scale manufacturing of reliable bipolar transistors.
- Devices are still manufactured in small volumes (primarily for direct part replacement and equipment maintenance)
- Some applications in low frequency, high-power circuits
- Examples include Al and In alloys with Si
- Can be done as an integral part of the growth process

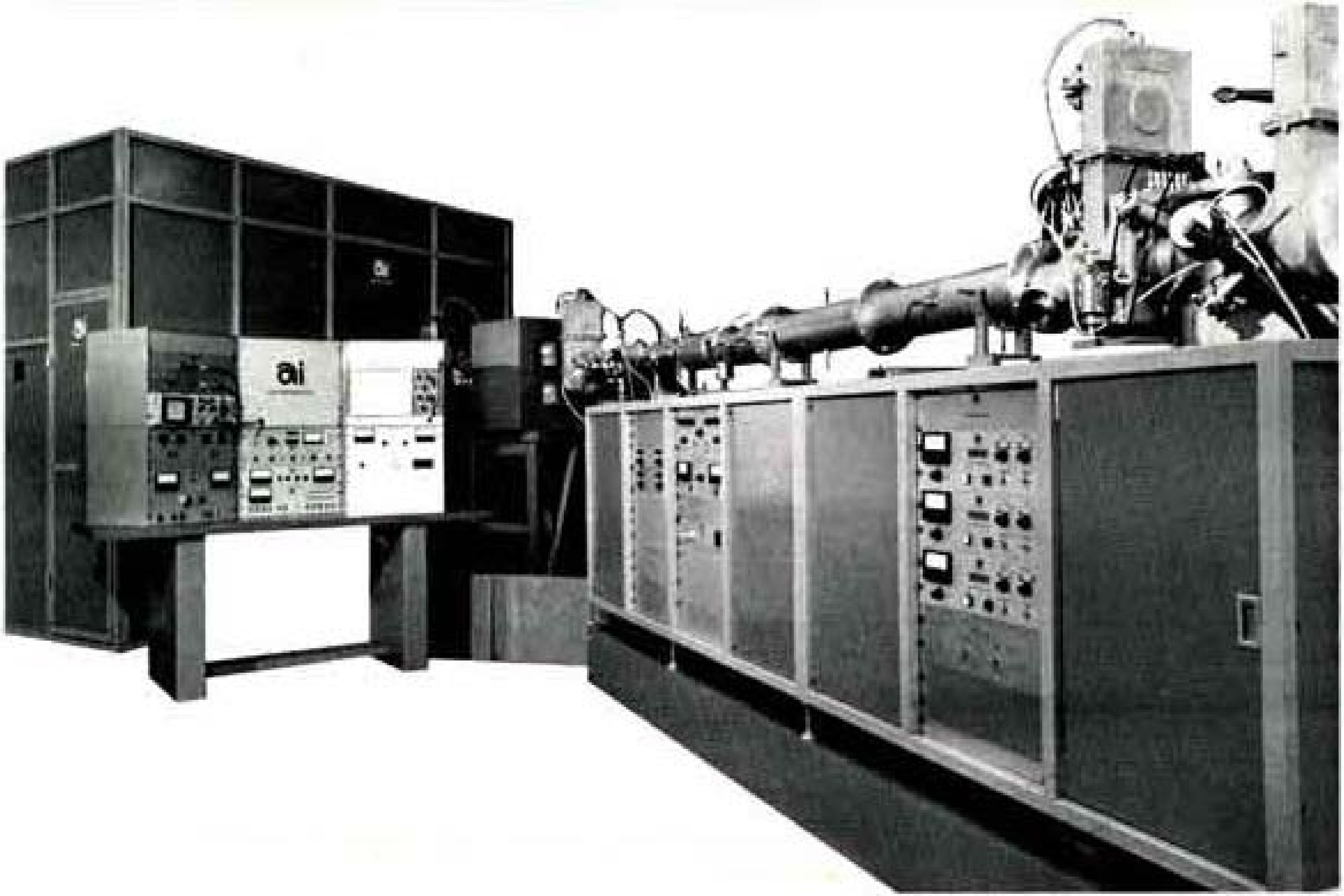
Diffusion

- Diffusion is a well controlled and largely exploited method for doping surface and near-surface semiconductor layers.
- Two distinctive variations exist: constant source diffusion, which creates somewhat sharper and shallower doping profile, and finite (limited) source diffusion, which creates smoother and deeper profiles.
- Various arrangements are possible, for the provision of lateral structuring, using diffusion-inhibiting masks, sacrificial layers, etc.
- Up to three or four distinct diffusion steps can be executed, in order to create complicated depth profiles with both p- and n-type regions, in for example bipolar integrated circuits.
- Currently diffusion is used mainly in combination with other methods

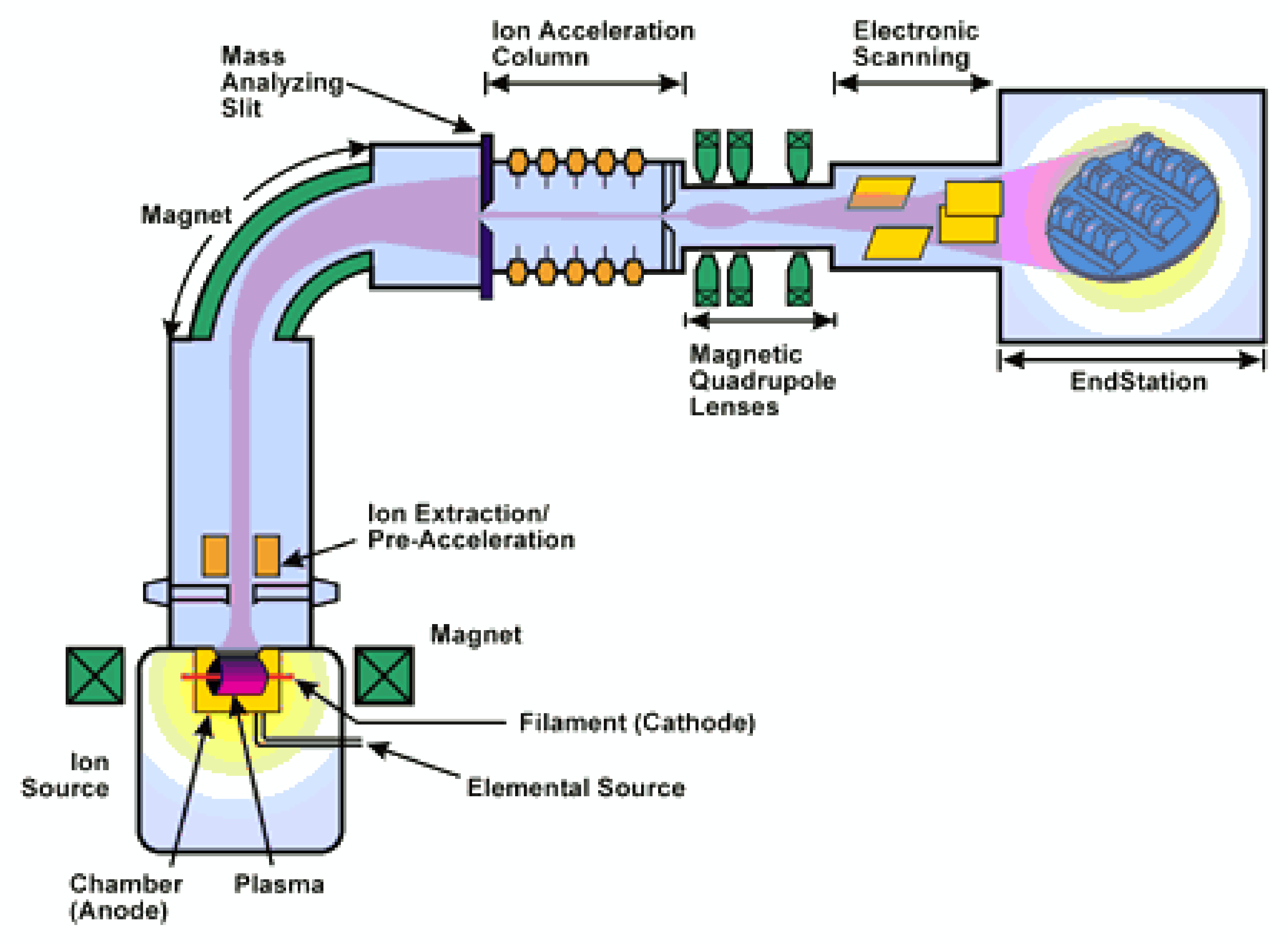
Ion Implantation

- Ion Implantation is used almost exclusively when a buried doping profile is to be created with a peek below the surface of the sample.
- It can be used by itself or in combination with other methods, for the creation of complicated graded doping profiles in high-performance single transistors and integrated circuits.
- Ion beams are typically produced in dedicated accelerators, with energies in the range (10 – 500 keV), resulting in depth of penetration of (10 nm – 1 μm).
- Apart from introducing the dopants, the implantation causes some structural damage the effects of which are usually mediated by appropriate post-irradiation annealing steps.
- Can be used for imaging of crystal grains (channeling)

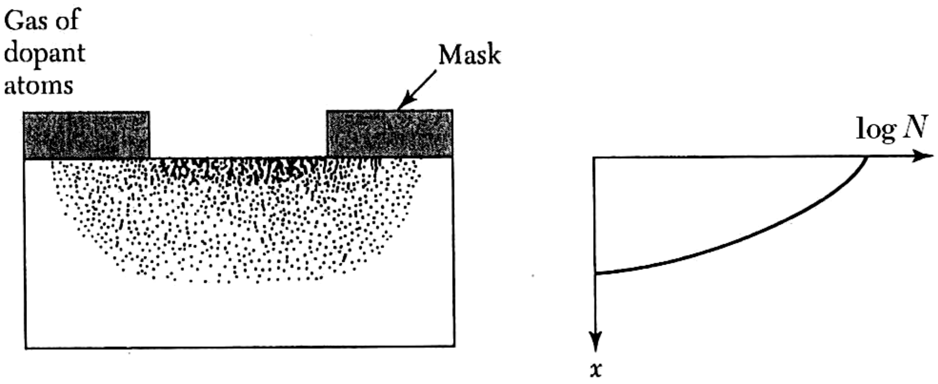
70’s Accelerators (now Veeco) 400 Ser.



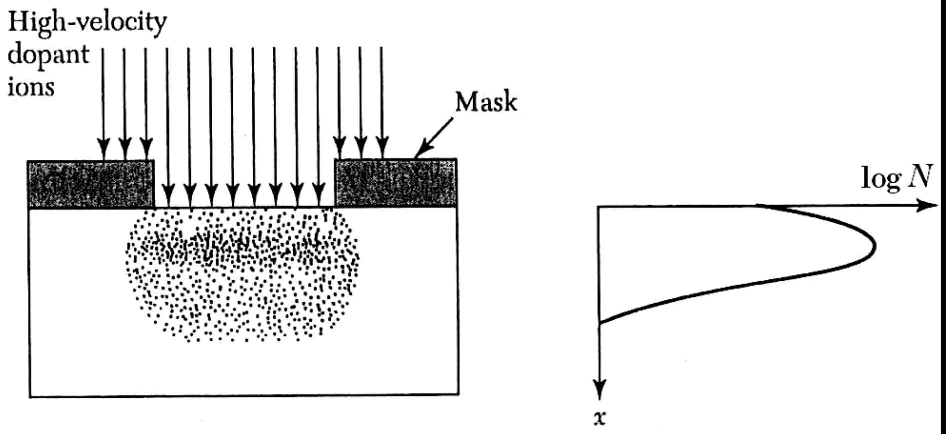
Rough Schematics of an Ion Implanter



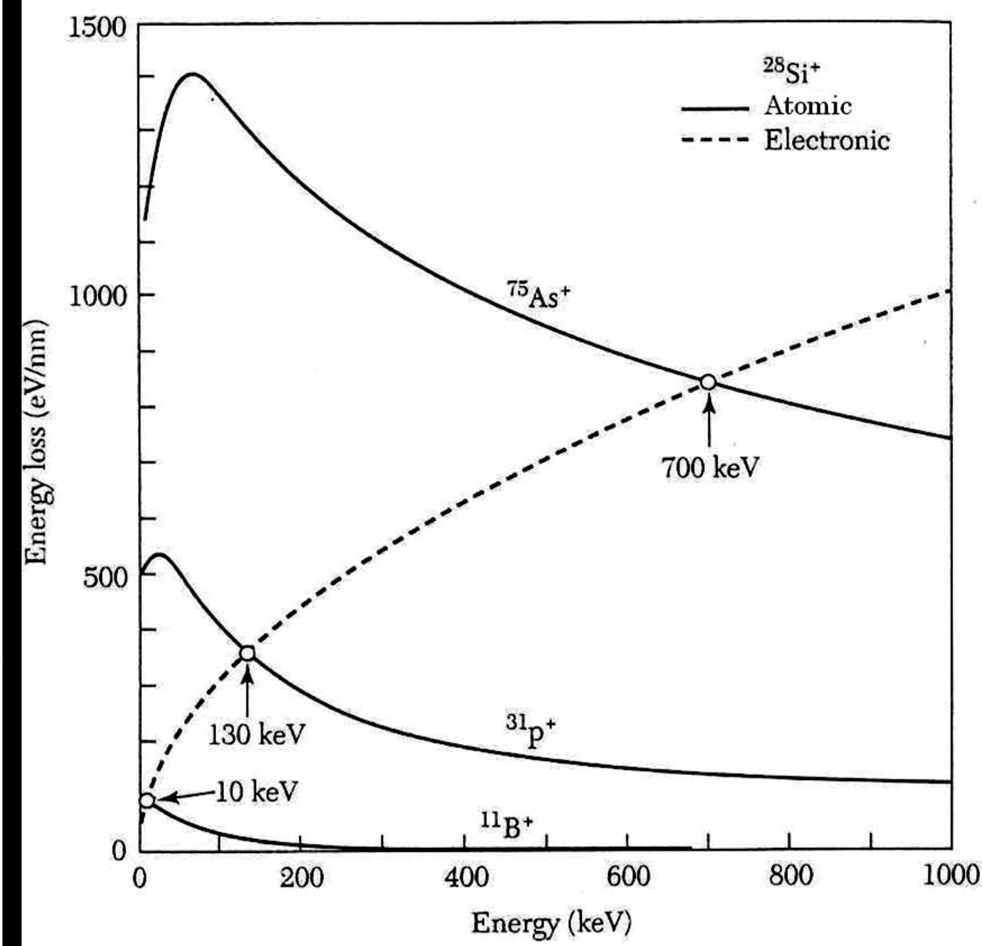
Ion Implantation Basics



(i) Diffusion

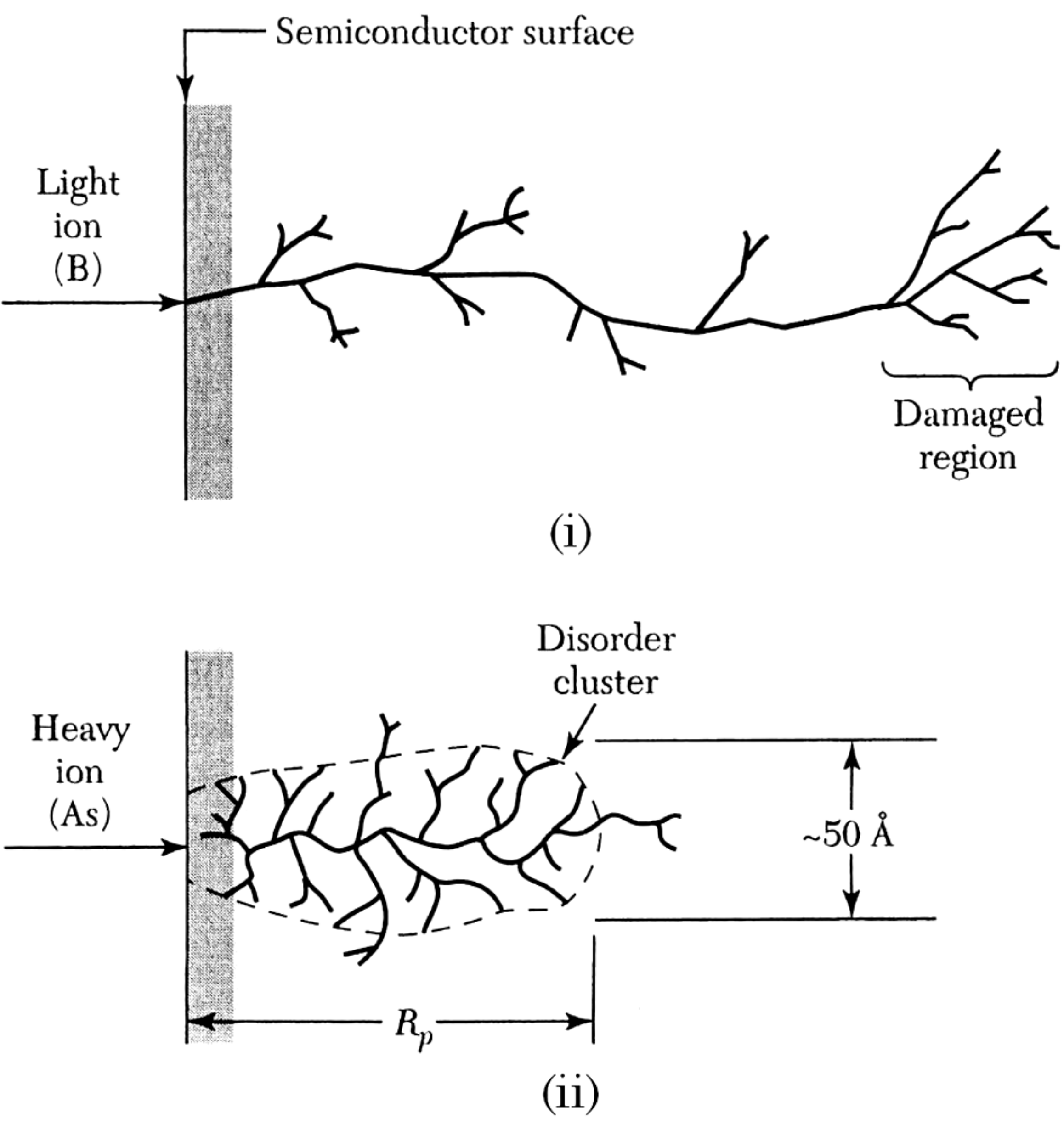


(ii) Ion implantation



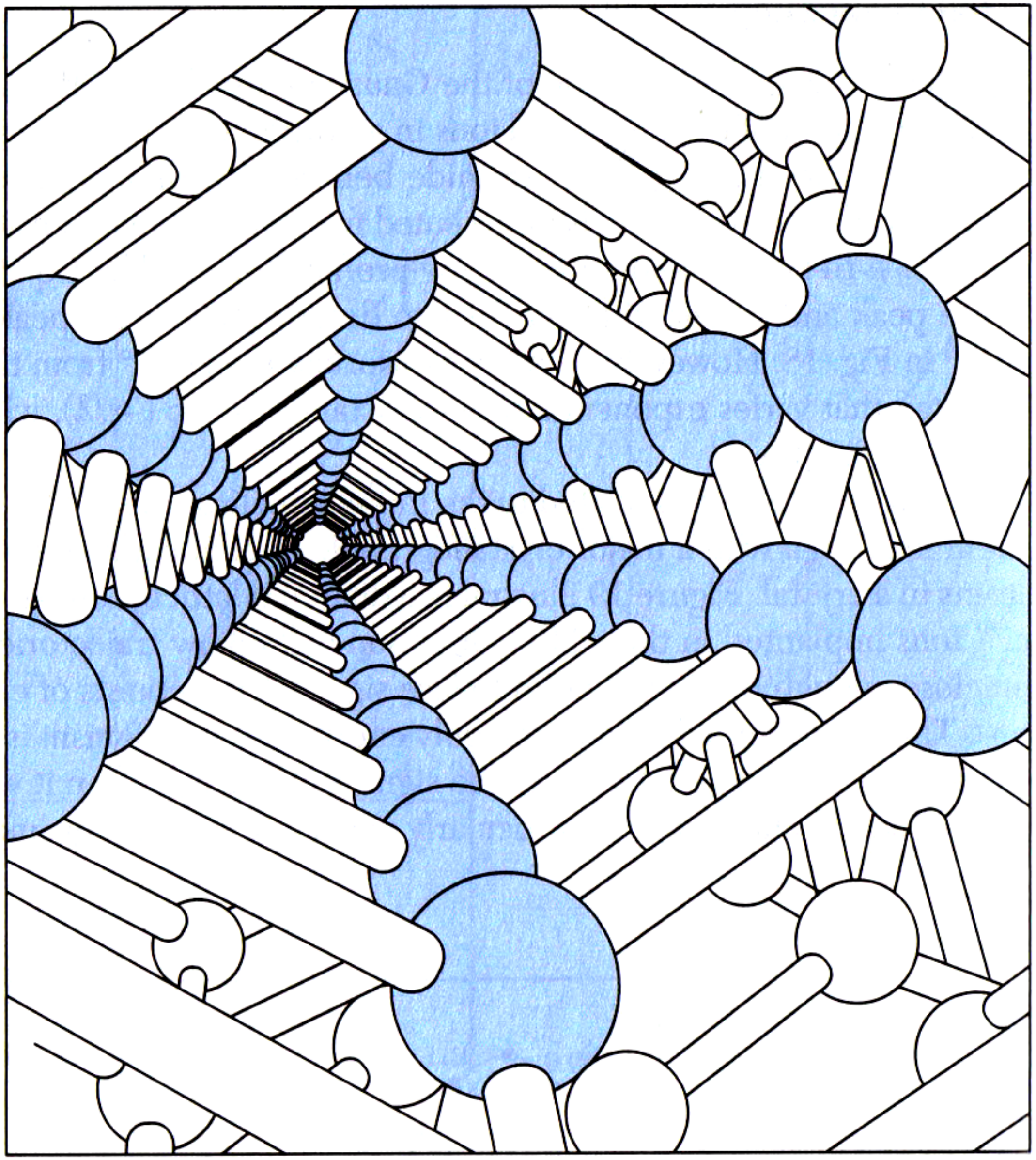
- Electronic collisions – producing electron-hole pairs (as collected when the crystal is used as a radiation detector)
- Atomic collisions with the lattice atoms – atomic displacements.

Penetration and Damage



- Light ions penetrate further, leaving a damaged (and implanted) region somewhat deeper below the surface.
- Heavy ions interact very strongly with the atoms, penetrating to shallower depths and leaving more concentrated damage.
- There are implications for imaging techniques, as well. Compare imaging with Ga or He ions and with electrons!

Channelling

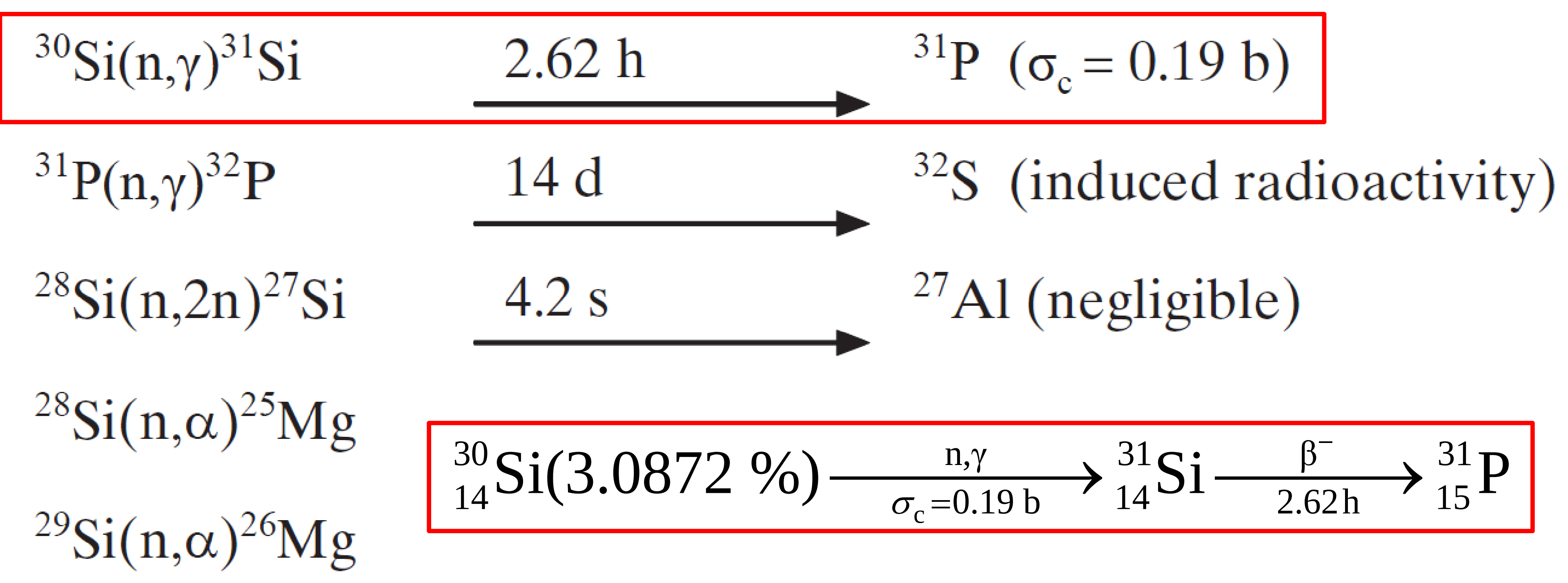


- The range of ions is increased dramatically when the beam is aligned well with respect to some major crystallographic directions <110> Si on figure.
- Channelling is usually minimized my on-purpose misaligning the ion beam at a small angle ~ 5 – 10 ^{o}. The depth profile would otherwise be severely degraded.
- SOI methods – Oxygen implantation technology.

Transmutation

- The most common use of transmutation doping is to do low or medium n-type doping of silicon.
- The process involves neutron irradiation, typically in research grade nuclear reactors, with high flux of thermal (moderated) neutrons.
- Usually phosphorous is produced, which is an efficient n-dopant (donor) in silicon.
- The advantages of the method are: excellent on-wafer radial and on-ingot longitudinal homogeneity, excellent control, especially at low doses and applicability to some common semiconductors: Si, GaAs, GaP, Ge and Se. Note the uses of radiation-hard semiconducting material (i. e. aero-space electronics).
- The main disadvantage is the relatively higher cost (it can sometimes double the cost of devices) and the slow throughput (it takes days to irradiate and deactivate to safe limits).

Neutron Transmutation - Principles



$$^{30}\mathrm{Si}(n,\gamma)^{31}\mathrm{Si} \xrightarrow{2.62\ \mathrm{h}} {}^{31}\mathrm{P}\ \ (\sigma_c = 0.19\ \mathrm{b})$$

$$^{31}\mathrm{P}(n,\gamma)^{32}\mathrm{P} \xrightarrow{14\ \mathrm{d}} {}^{32}\mathrm{S}\ \ \text{(induced radioactivity)}$$

$$^{28}\mathrm{Si}(n,2n)^{27}\mathrm{Si} \xrightarrow{4.2\ \mathrm{s}} {}^{27}\mathrm{Al}\ \text{(negligible)}$$

$$^{28}\mathrm{Si}(n,\alpha)^{25}\mathrm{Mg}$$

$$^{29}\mathrm{Si}(n,\alpha)^{26}\mathrm{Mg}$$

$$^{30}_{14}\mathrm{Si}(3.0872\ \%) \xrightarrow[\sigma_c=0.19\ \mathrm{b}]{n,\gamma} {}^{31}_{14}\mathrm{Si} \xrightarrow[2.62\,\mathrm{h}]{\beta^-} {}^{31}_{15}\mathrm{P}$$

- The most relevant nuclear reaction path is the neutron capture accompanied with gamma emission and successive transmutation to phosphorus and corresponding beta minus emission.
- The abundances of the different natural isotopes of Si are:

  ^{28}Si (92.2 %), ^{29}Si (4.7 %) and ^{30}Si (3.1 %)
- On the order of 10 ppm of ^{31}P need to be created for $\rho \sim 50$ Ω.cm.

Transmutation in Research Reactors

- Often rotation and/or translation is necessary to achieve the best possible homogeneity of irradiation.

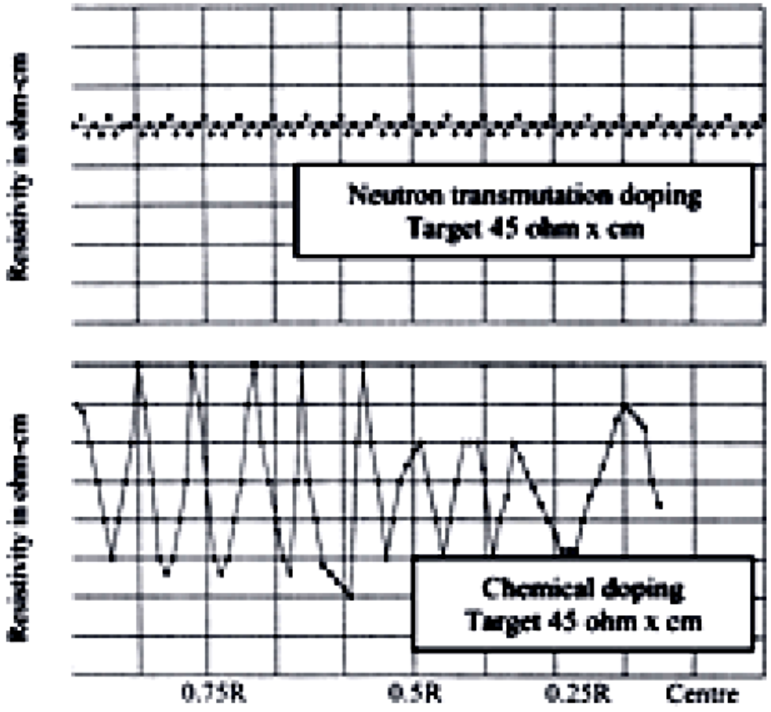
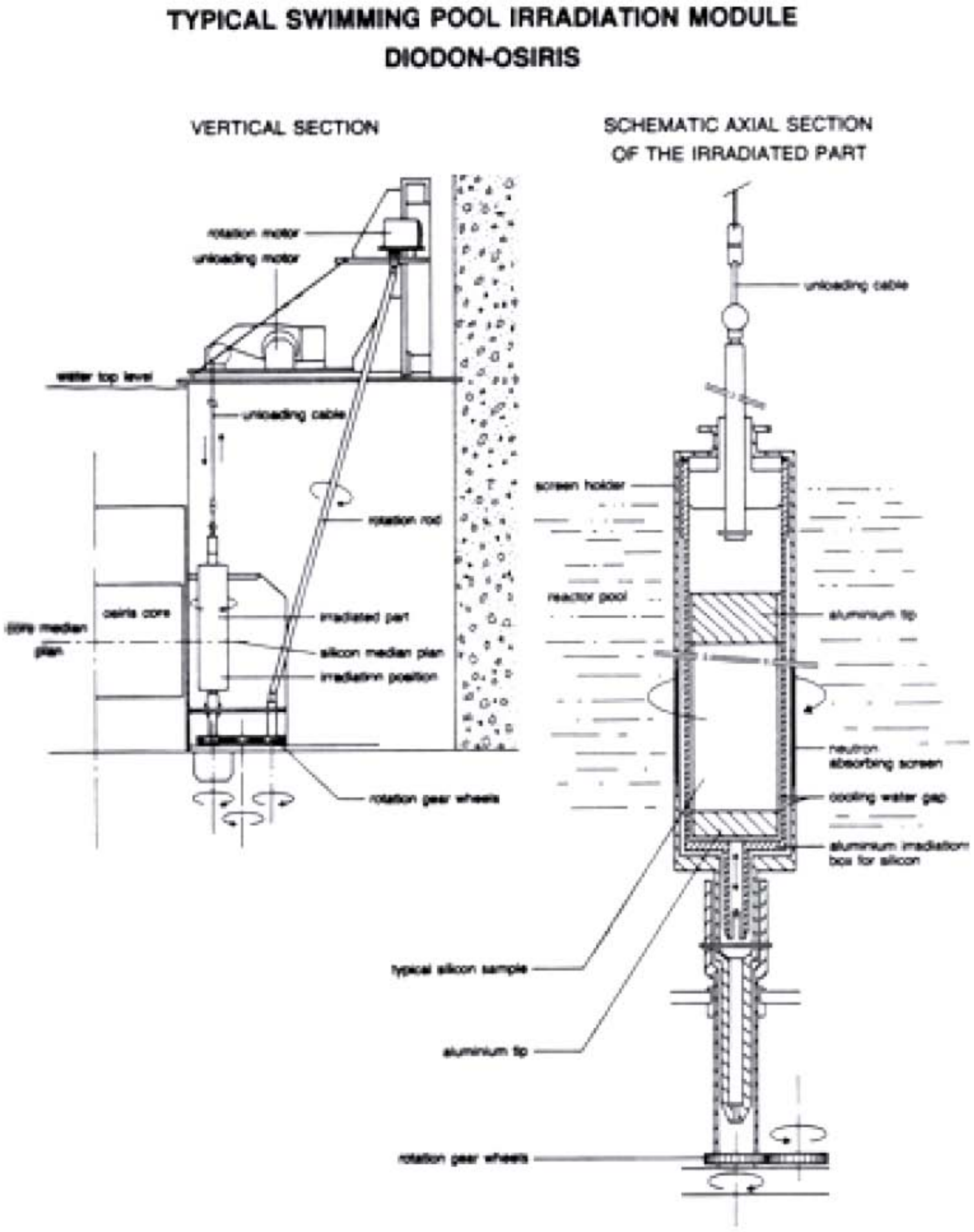
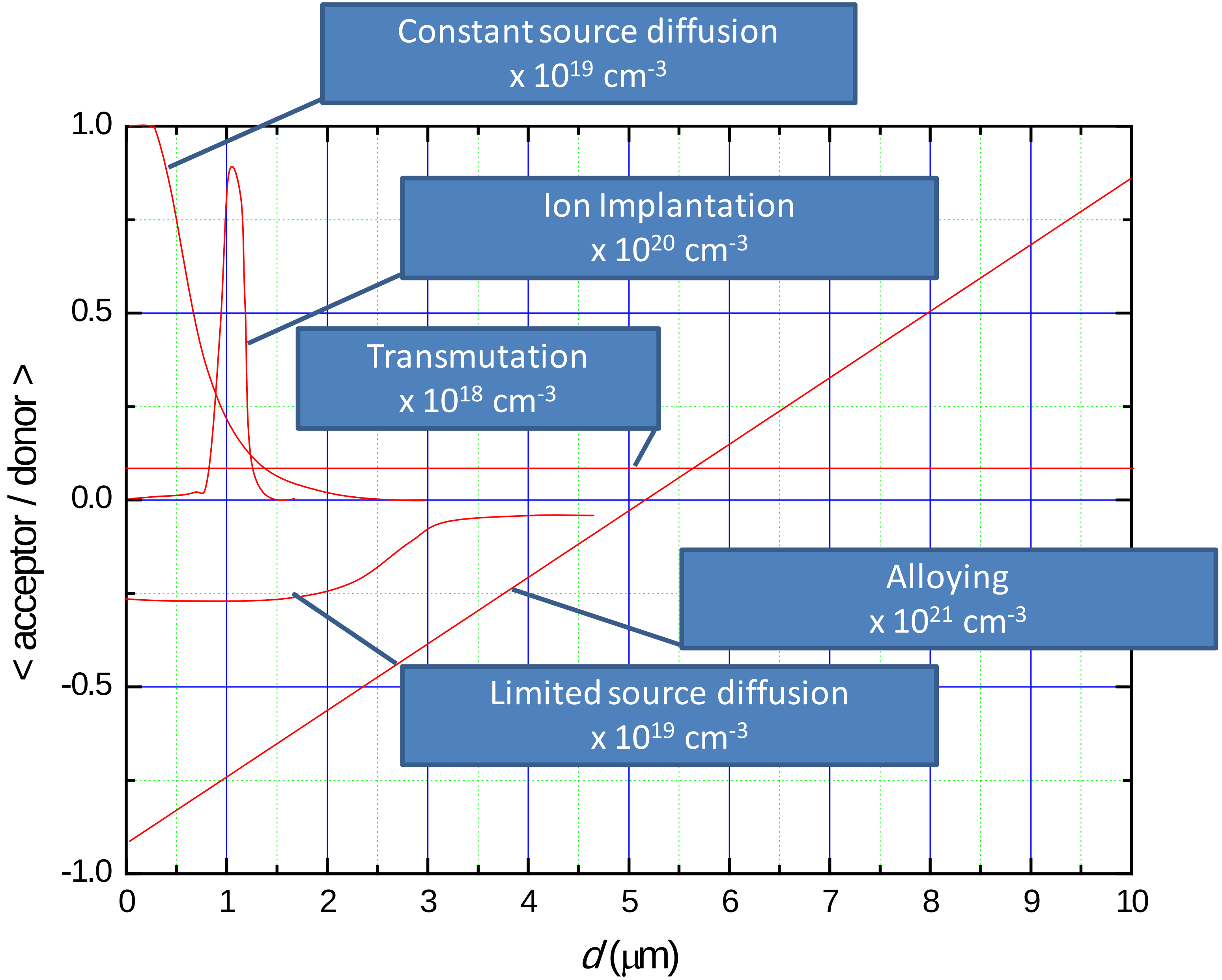


FIG. 2. Variation of radial resistivity after neutron transmutation and chemical doping, respectively.



Rough Depth Profiles



Constant source diffusion
x 10^{19} cm^{-3}

Ion Implantation
x 10^{20} cm^{-3}

Transmutation
x 10^{18} cm^{-3}

Alloying
x 10^{21} cm^{-3}

Limited source diffusion
x 10^{19} cm^{-3}

Elemental vs. Compound Semiconductors

- Elemental:
  - Classical: Si, Ge
  - Historic: Se (gray selenium)
  - Research: C (doped diamond)
- Compound:
  - III-V:
    - Ga-based: GaP, <u>GaAs</u>, GaSb
    - In-based: InP, InAs, InSb
    - Nitrides: AlN (direct wide gap), BN (indirect widegap), InN and GaN (direct intermediate gap)
  - II-VI: CdTe, CdSe (semiconducting), HgTe, HgSe (semimetals), ZnS, ZnSe (widegaps)

III-V Semiconductors - GaAs

- In very high speed devices compound semiconductors are normally used instead of silicon or germanium.
- One of these semiconductors is gallium arsenide, GaAs.
- This is a III-V material, with a zinc blende structure, i.e. two interleaved f.c.c. lattices, one of Ga, the other of As, with a Ga atom at the centre of a tetrahedron of As atoms and *vice-versa*. Energy gap $E_g = 1.4$ eV.
- Values of mobility in GaAs and Si at low/medium fields (high-field properties are discussed later):
- Electrons: $\mu_n = 0.92$ (GaAs) and 0.14 (Si) $m^2\,V^{-1}\,s^{-1}$
- Holes: $\mu_p = 0.03$ (GaAs) and 0.05 (Si) $m^2\,V^{-1}\,s^{-1}$
- Note, that GaAs *n*-channel FETs (described later) are very fast, but *p*-channel FETs are not. One more reason why CMOS is not practical in GaAs.

GaAs - Problems

- *n*-channel devices can operate at > 100 GHz, giving applications in satellite receiver amplifiers, radar, radio astronomy, mobile phone communications…
- Fast CMOS-type logic circuits with low power consumption are not possible, because μ_p is low.
- Crystal growth (Czochralski method difficulties) vapour pressure differences
- GaAs wafers are more fragile, limiting diameters to ~ 150 mm or so, depending on defect count requirements.
- Toxicity of As – at high temperatures As tends to vaporise from the GaAs surface.
- Dopant diffusion is more difficult – ion implantation is often used instead, in order to minimize exposure to high temperatures.
- The world could run out of Gallium (19 ppm natural abundance).

Thanks and Acknowledgements

Thank You Very Much for Your Attention!