Applications of ion beams in materials science

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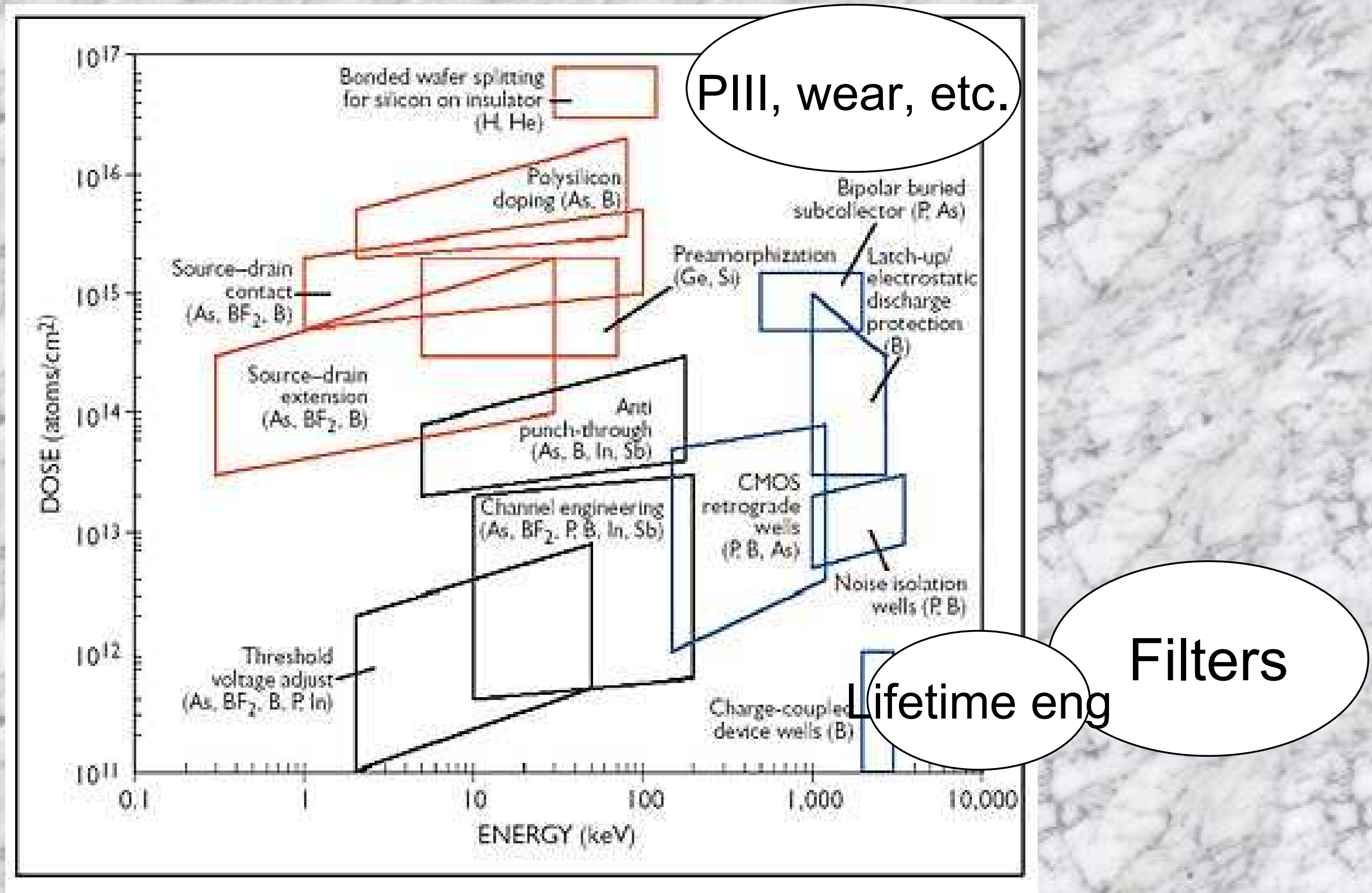
Types of processing technologies

- Top-down - waste of energy
  - Stone age tools
  - metals: cast and turned
- Bottom-up - preferred
  - antique glass,
  - in IC: planar processing, e.g., implantation, CVD, oxidation, metallization
  - ultimate: nanotechnology

Ion beams as a tool

- Despite of damaging, as consequence of its non-equilibrium nature, ion beams became standard doping, modifying and analytic tools
- Especially, in IC technology: implantation, apart from lithography, is the most used technology. In Intel’s new processor 23 implantations!
- Energy there ranges from few MeV to today’s 100 eV, in niche applications, up to few 100 MeV
- Results of the next talk summarize achievements in cooperation of Russian and Hungarian partners using ions with 'extreme' energies

Dose-energy requirements, IC and others



Physical features of ion-solid interactions

- Production of
  - point defects – lifetime and damage engineering, Single Event Upset, nuclear filters
  - defect clusters – nanodots – phase separation
  - amorphization – device isolation (solar cells)
- Sputtering – FIB, TEM sample, SIMS-Auger
- Chemistry by implanted atoms – SIMOX, Mixing, catalysis
- Resumed crystallinity - reliable implantation
- …in all combinations
- Think also of ion beam analysis (IBA) techniques

Physics behind

- Doubly statistical nature of ion beam effects:
  - location of impinge is random,
  - stopping process, the cascade itself, too
- Difference of effects of electronic *vs.* nuclear stopping – more complicated than anticipated
- Thermal picture, planar geometry, laser or ion pulses: margin in resolidification velocity:

  crystalline *vs.* amorphous regrowth: < vs. >15 m/s
- Equivalent to an (inverse) rate 10 ps/elementary cell, the time necessary to establish a perfect chemical bond

Ions in Semiconductors

- Silicon device – full success, SiC – only solution for doping, others – less success
- Implantation Preamorphization doping, “dual doping” (Caltech-KFKI)
- Roadmap demands – R_p = 20 nm
- Solutions for year 2010 – SiGe, 3D gates, etc.

The low energy end

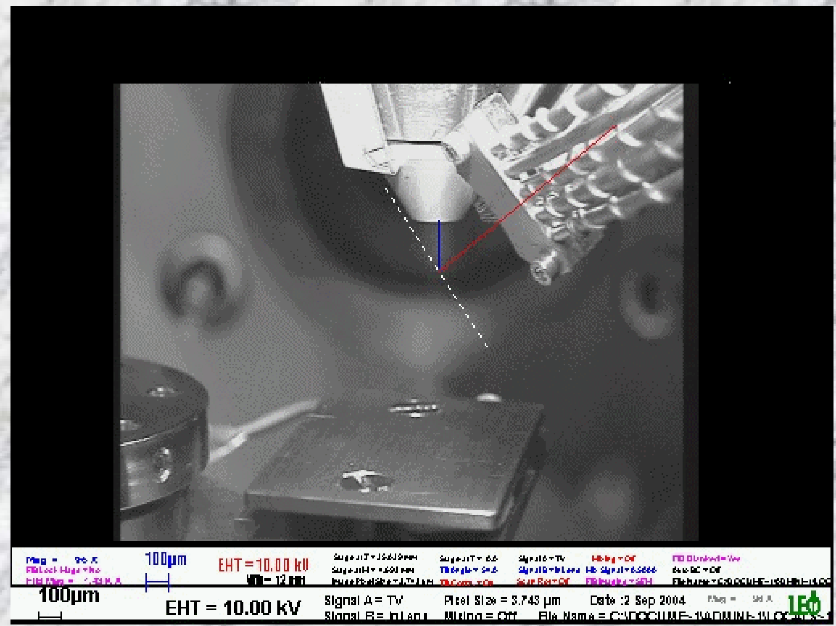
- Extreme low energies
- Difficulty in achieving high enough intensity beams at few hundred eV
- Molecular ions – from early BF_2^+ to decaborane ($B_{10}H_{12}$)
- Cluster ion deposition

Sputtering – why towards extreme low energies?

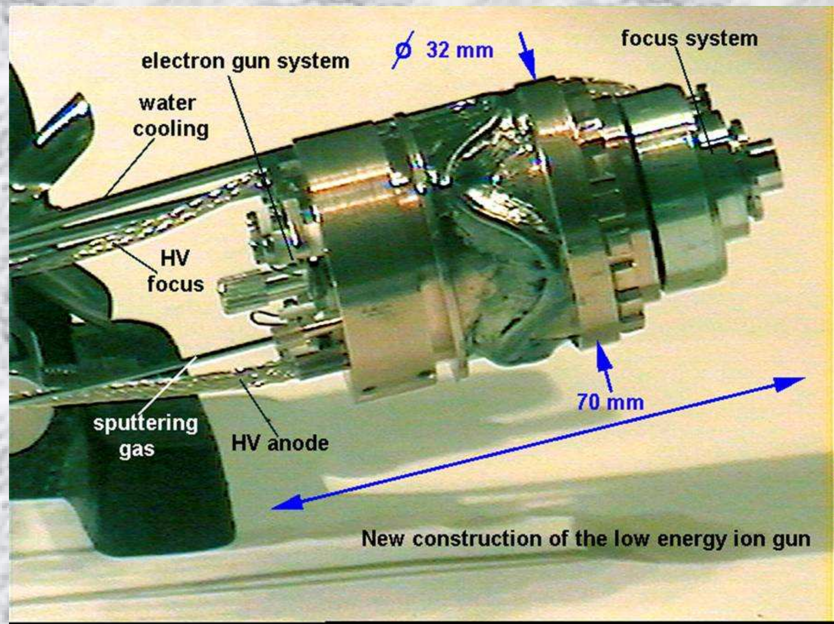
- Ion implantation – a 'sloppy' sputtering
- Atoms are removed, but as ΔRp is not very much different from R_p, defects accompany
- good if part of the cascade is out of the target
- If sputtering is the goal, defects count as artefact
- Main areas of ion beam sputtering: FIB, TEM
- Solution: reduce energy, collimate, but
- with lower energies, both sputtering rate and efficiency will be reduced

Sputtering applications

- FIB



- TEM

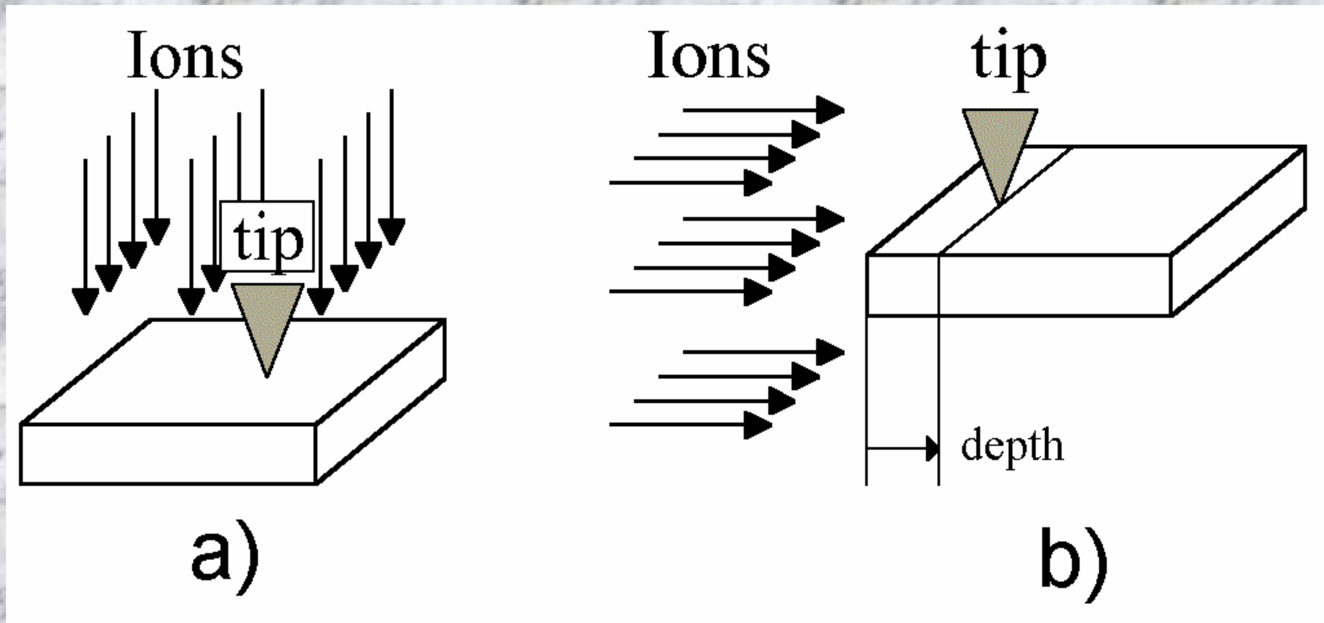


Comparison of expected differences for low and high energies

- Surface *vs* thin film, even buried layers
- I.e., cascade volume partly out, or buried inside
- Heat balance – radiation may play a role
- Ambient effects for low energies, especially, oxygen

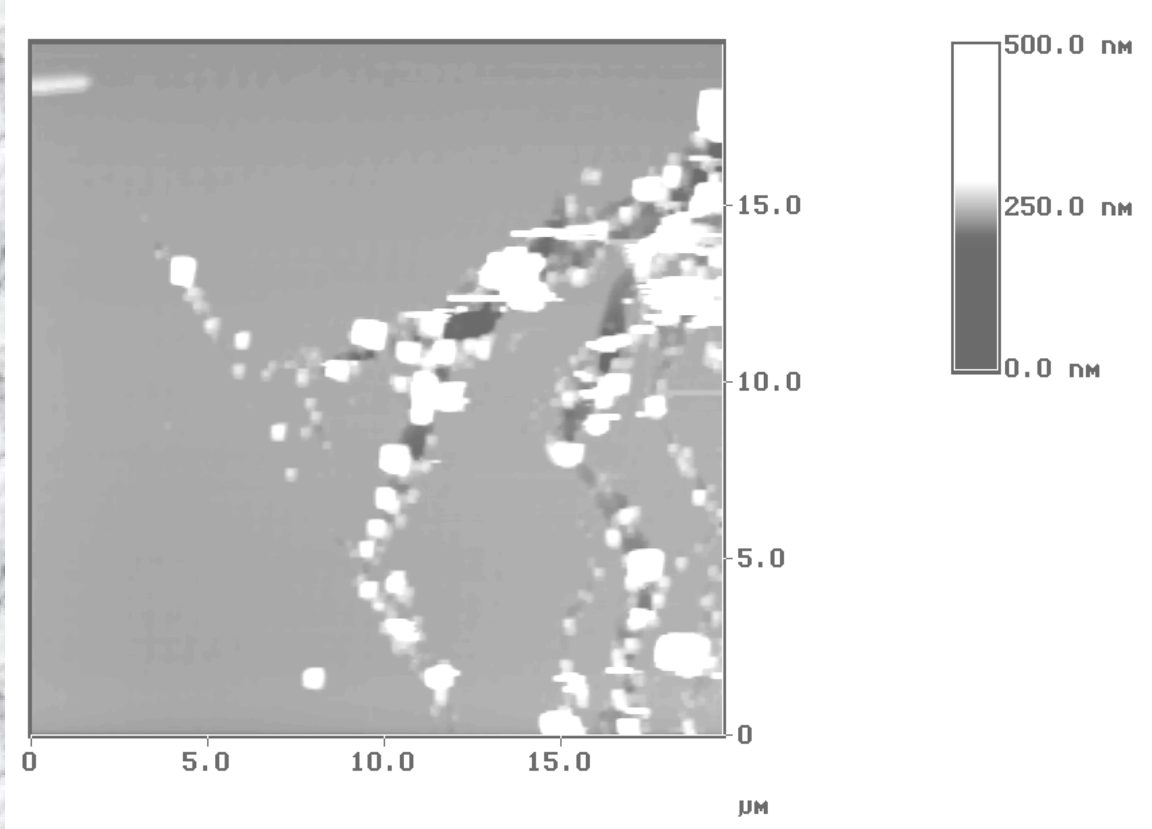
Heavy ions at extreme high energies

- Electronic stopping adds to defect production
- Irradiation geometries: normal and parallel



Atomic processes for a single cascade

- CM-AFM of a cascade branching in mica for Ne 217 MeV *(L.P. Biró, J. Gyulai, and K. Havancsák: Vacuum 50(1998)263)*



Irradiation of Highly Oriented Pyrolytic Graphite, HOPG

- Nanotubes form
- Length around 10 μm
- As cascade duration is some 10 ps, growth rate is around sound velocity
- Condensation of vapor or rolling up of graphene sheets – this determines metallic or semiconducting properties

As-formed nanotube

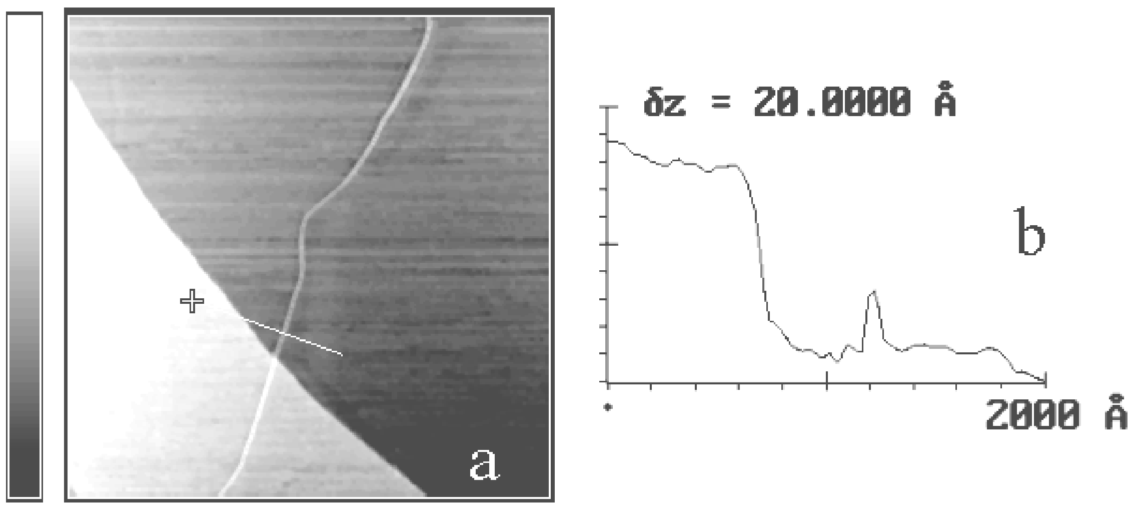
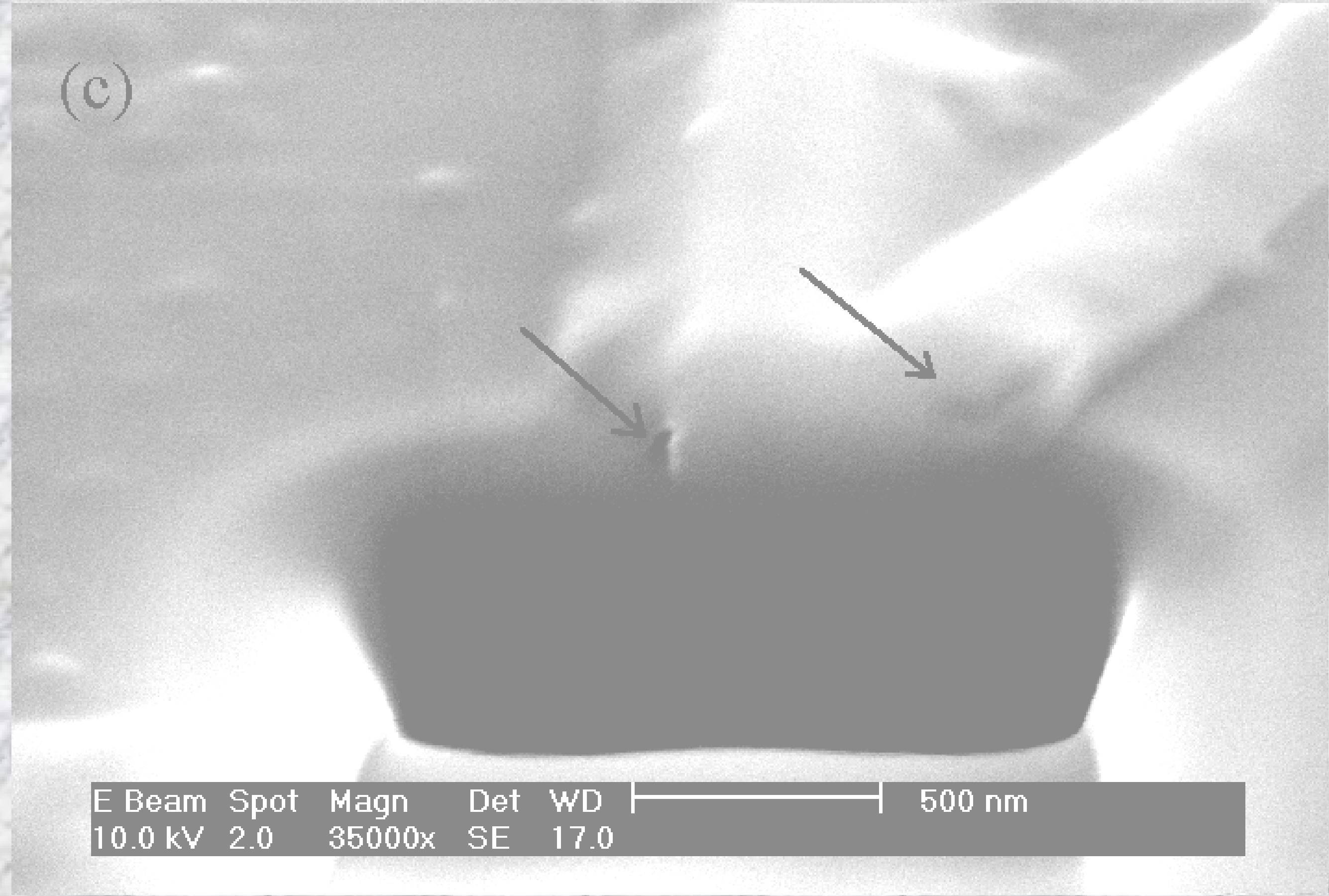


Fig. 2

FIB (Focused Ion Beam) sectioning



Conclusions

- Implantation stays with us, at least for good ten years
- Strategy for a small insitute: to find "niches"
- At the low energy end, doping and sputter removal
- High end led us to nanotubes, still are problems to be solved