

Lattice location of implanted ions and characterization of implantation- induced damage in Ge



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Outline



Lattice location of implanted ions in Ge

- Motivation
- Emission Channeling technique (EC)
- Experimental details
- Experimental results
- Conclusions

Motivation

Lattice location of implanted ions in Ge

"ION IMPLANTATION IN GE"

Where do the ions end up?

What happens to the lattice?

lattice location of impurities (a.f.o. annealing temperature)

structural damage (i.e. Ge-displacements, vacancies, strain, amorphization...)

electrical damage (i.e. defects in lattice can introduce deep defect levels in the bandgap)

Motivation

Lattice location of implanted ions in Ge

“ION IMPLANTATION IN GE”

« Why Germanium:

- high free carrier mobility (Si x 3)
- low activation energy

« Why ion implantation:

- most widely used technique to dope semiconductors
- good control of profile & amount of dopants

« Problems:

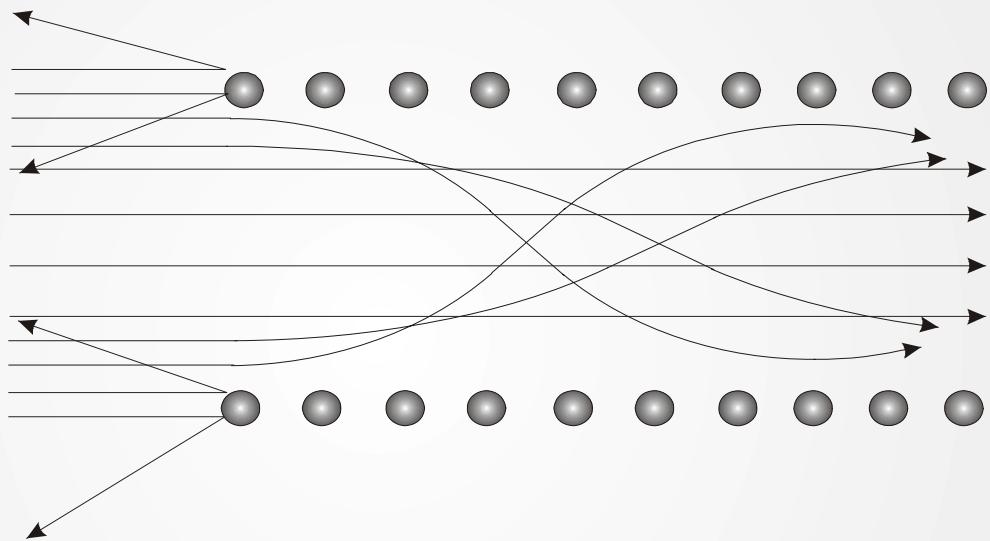
- creation of lattice damage
- activation of dopants → lattice location

Emission Channeling

Lattice location of implanted ions in Ge

« Conventional channeling (RBS/C)

- ➔ Use of **positive** ions
- ➔ Due to repulsive Coulomb force with lattice atoms, ions channel **in between** of rows of atoms



Emission Channeling

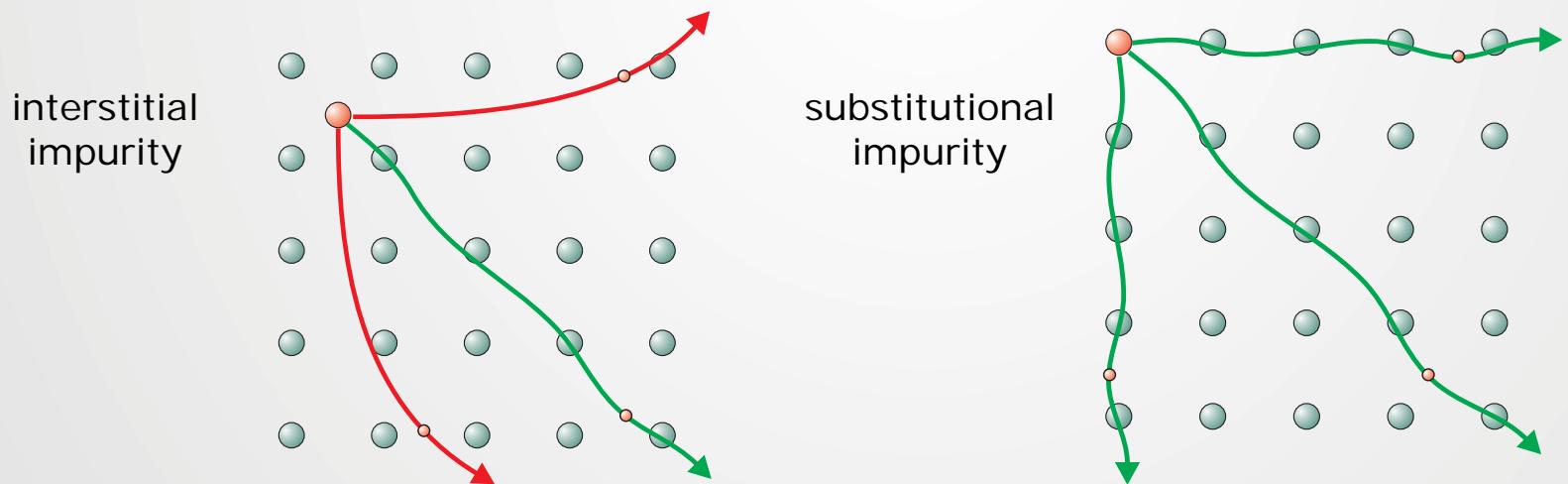
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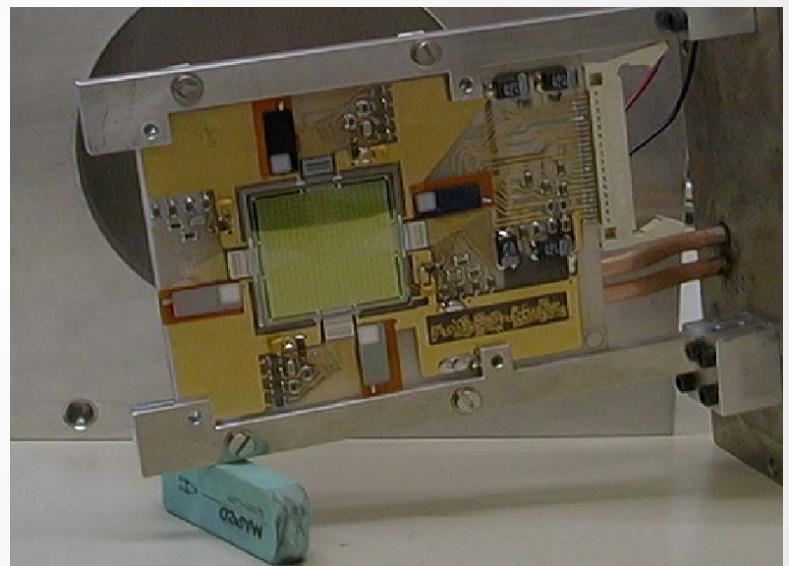
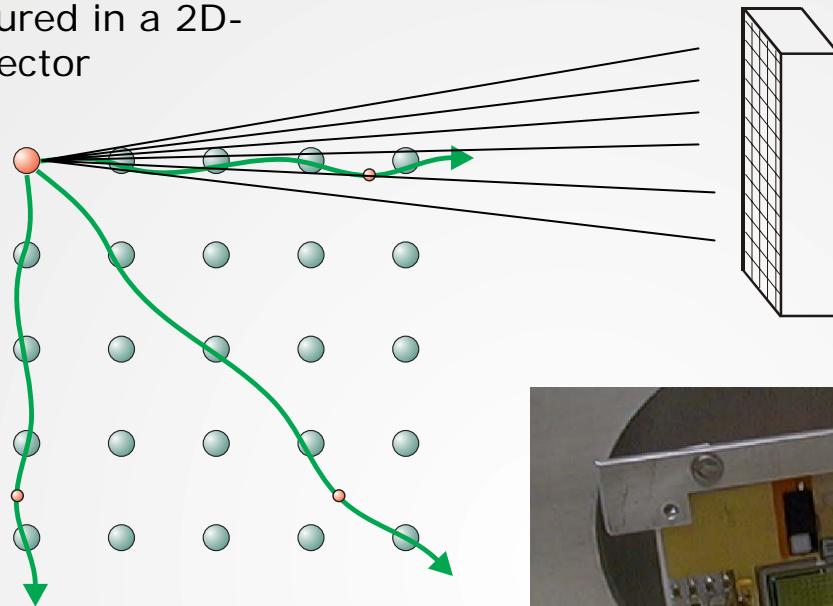
- ➔ Use of **negatively charged** particles (electrons)
- ➔ Due to attractive Coulomb force with lattice atoms, electrons will channel **along** row of atoms
- ➔ Implantation of radioactive (β^- or CE) isotopes of element under investigation
- ➔ Study of e^- -emission determines lattice location of radioactive ion



Emission Channeling

Lattice location of implanted ions in Ge

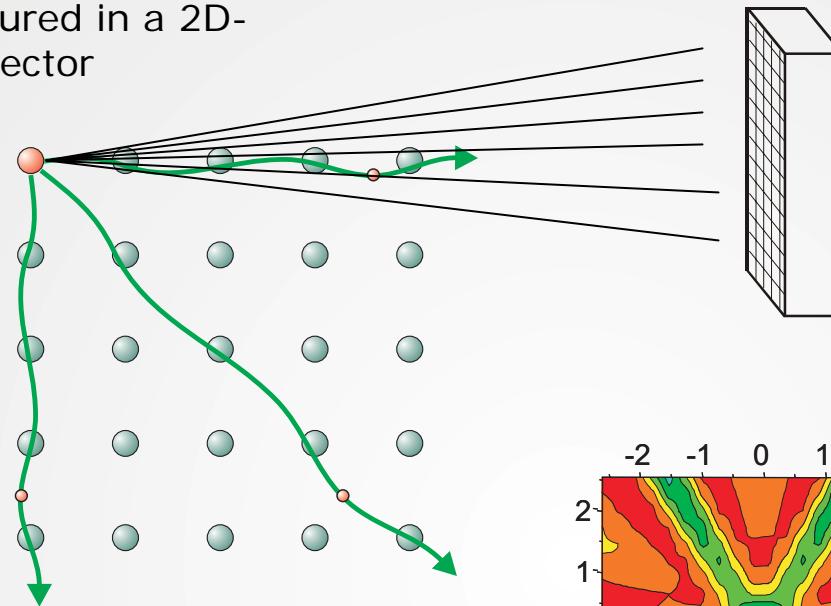
« Electrons are measured in a 2D-position sensitive detector



Emission Channeling

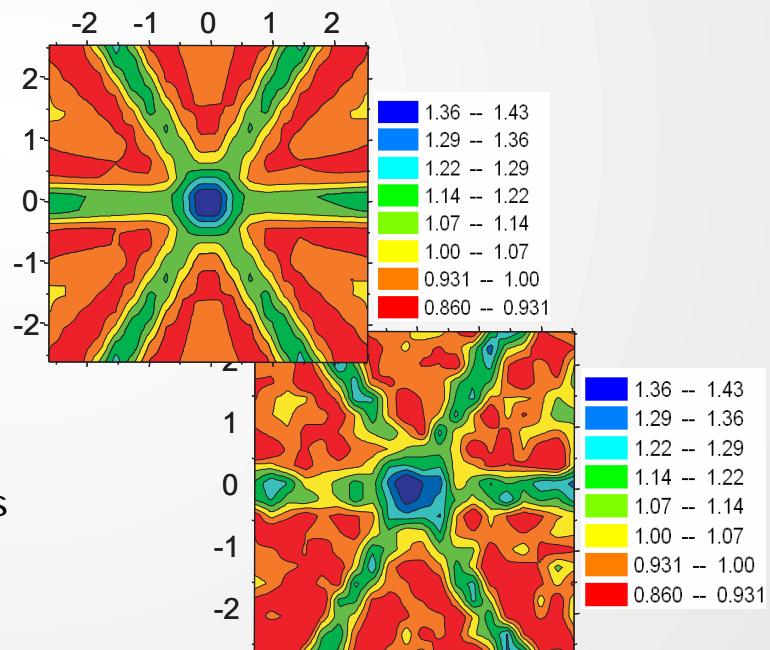
Lattice location of implanted ions in Ge

« Electrons are measured in a 2D-position sensitive detector



« Comparison between measured patterns
and simulated patterns

→ determination of lattice location of impurities



Experimental details

Lattice location of implanted ions in Ge

« implantations - @ ISOLDE

- 60 keV
- half life 20h → 50 days
- fluence $3 \times 10^{12} \rightarrow 2 \times 10^{13}$ at/cm²

« measurements - offline

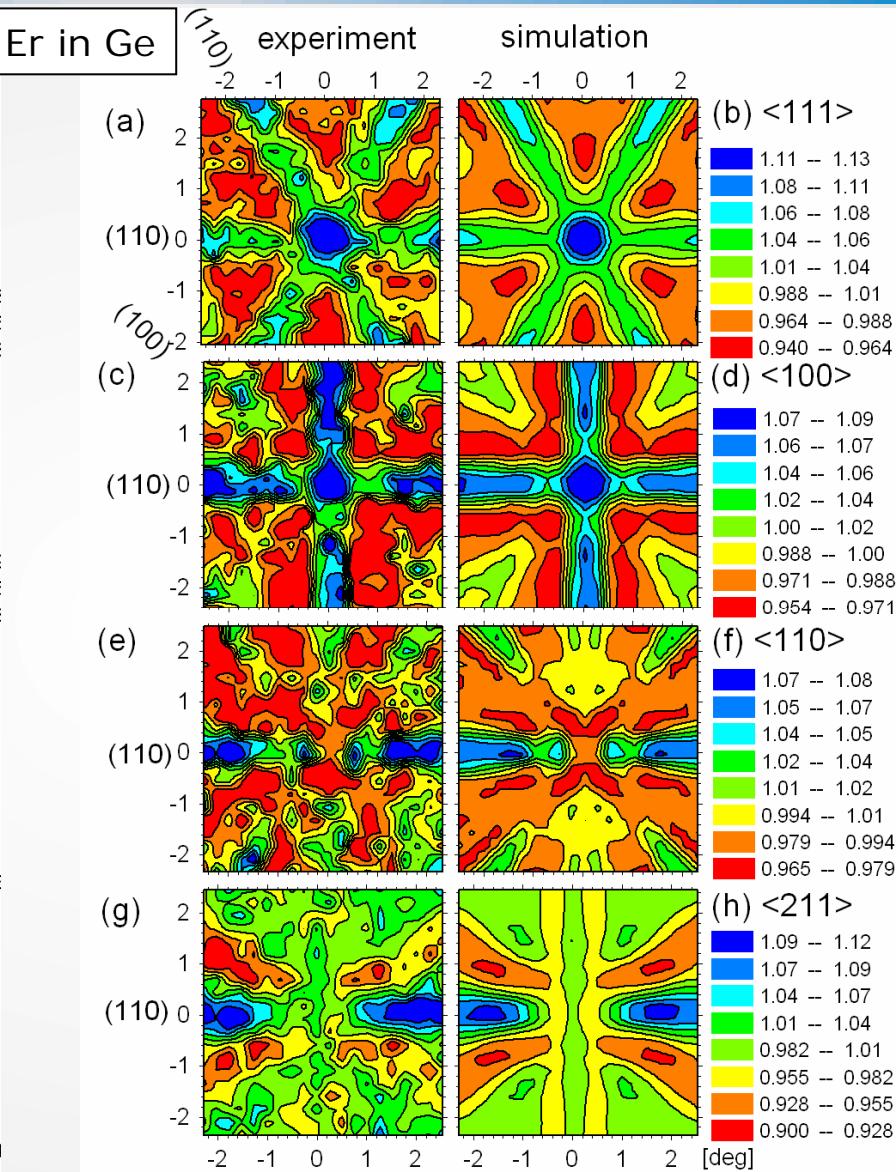
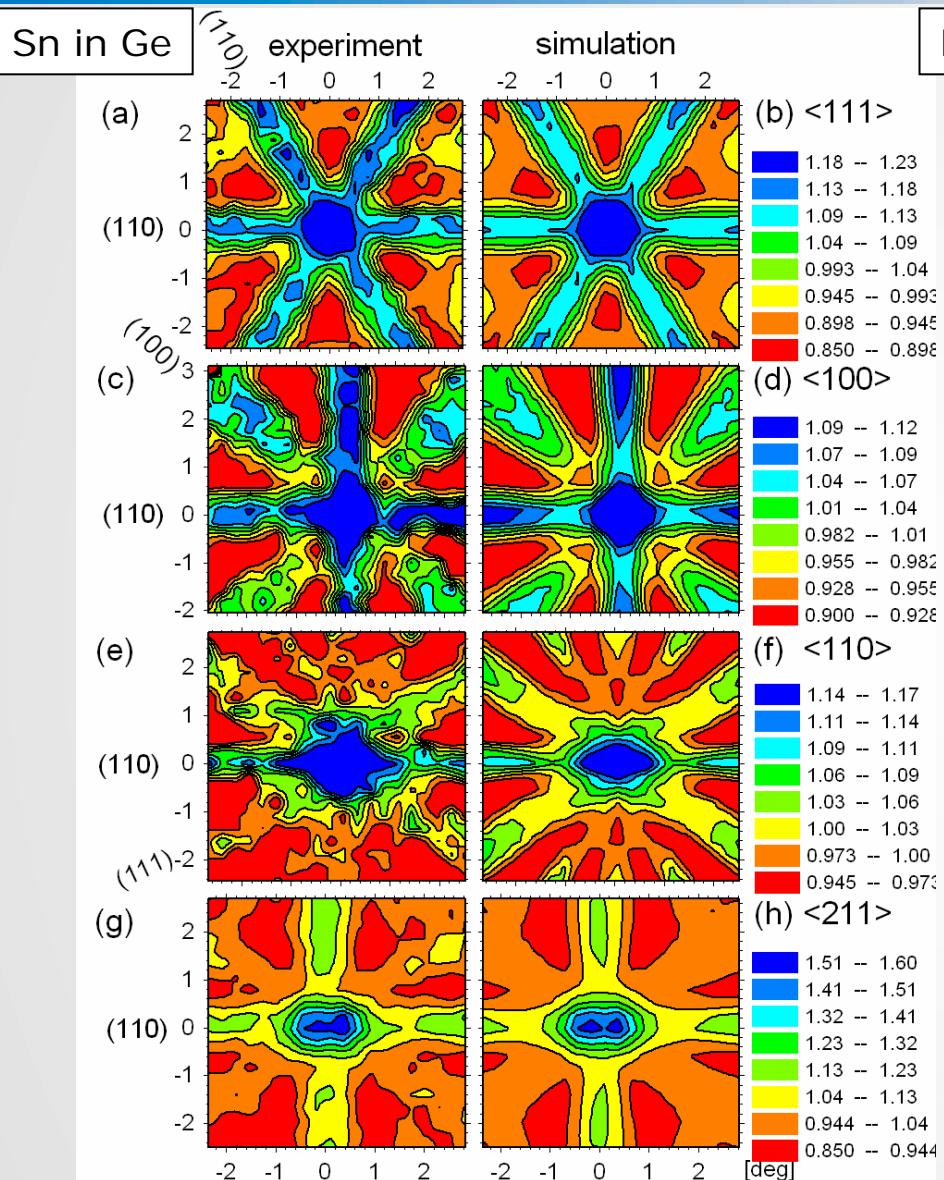
- at room temperature
- as implanted & after annealing up to 600°C (10min in vacuum)
- 4 different directions: <111>, <100>, <110> and <211>

« used isotopes - ²⁴Na

- ⁵⁹Fe
- ⁶⁷Cu
- ¹¹¹In
- ¹¹¹Ag
- ¹²¹Sn
- ¹⁶⁷Er

Experimental details

Lattice location of implanted ions in Ge

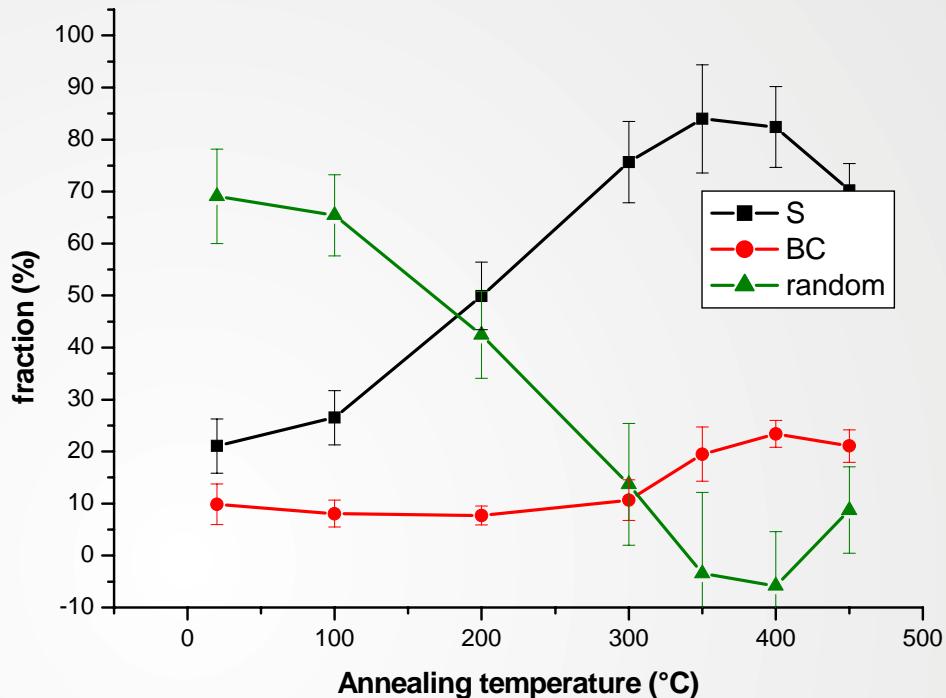
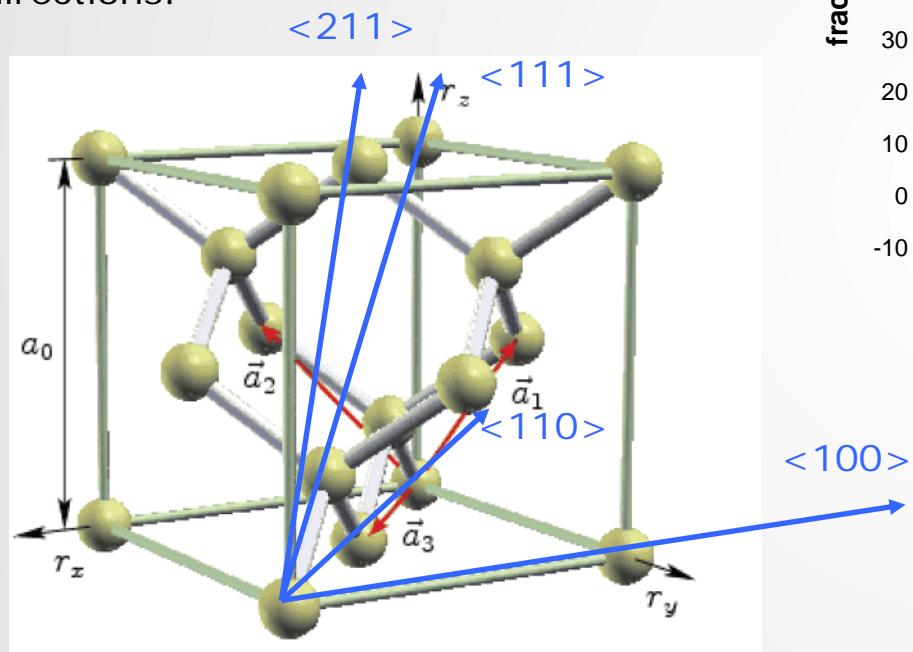


Experimental results

Lattice location of implanted ions in Ge

Case-study → ^{121}Sn in Ge

- « annealing up to 450°C
- « best fit with 2 lattice sites: substitutional (**S**) and bond-centered (**BC**)
- « fractions and sites are consistent in all 4 directions!

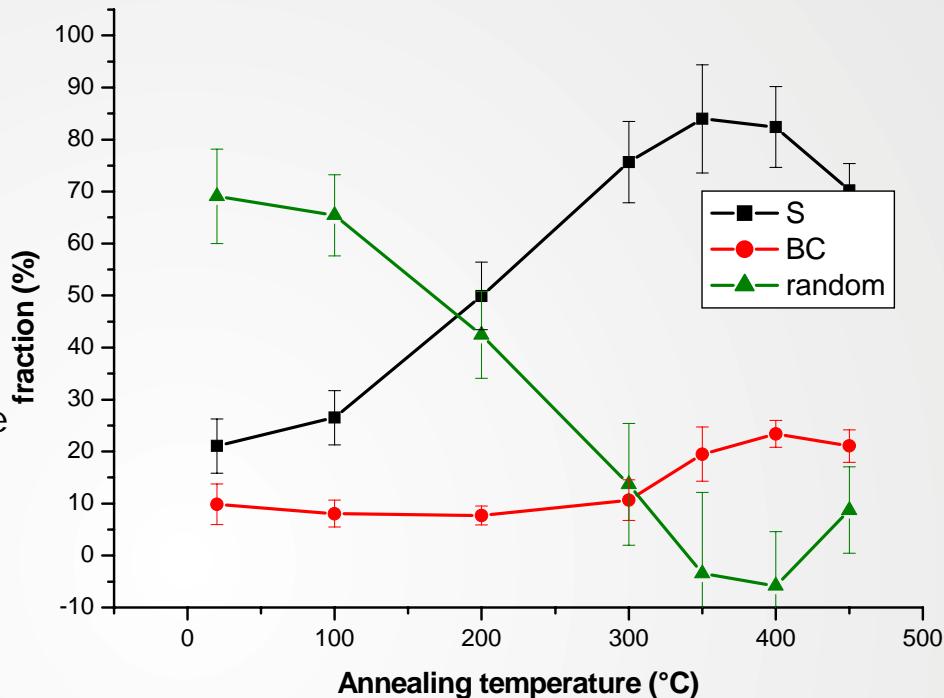


Experimental results

Lattice location of implanted ions in Ge

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- « annealing up to 450°C
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- « fractions and sites are consistent in all 4 directions!
- « annealing $>100^\circ\text{C}$ starts to remove 'lattice damage' (V_2 breaks up...)
- « after annealing @ 450°C: possible diffusion of Sn – interpretation of results changes!



- « **S** → largest fraction because Sn is group-IV element
→ chemically, S is the logical lattice site (definitely in perfect crystal)
- « **BC** → in between of two S-sites
→ possible explanation of 'exotic' BC-site
 - vacancies (V) and Ge-interstitials (I) are mobile at -70°C
 - capture of V or I by Sn → Sn-V or Sn-I complex → BC site?

Theoretical evidence for BC-site?

- « From literature → so far, 2 theoretical groups tried to tackle the question "what happens if a vacancy gets captured by an impurity in Ge (and Si)"

Höhler et al. (Jülich)

- 1) Al, P, Ga, As, Se occupy S-position and V stays on a nn-S-position (*)
- 2) Cd, In, Sn, Sb, Bi move to the BC site with V 'split' between 2 S-sites (*)

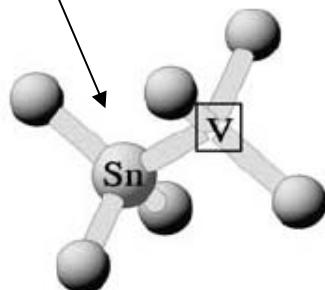


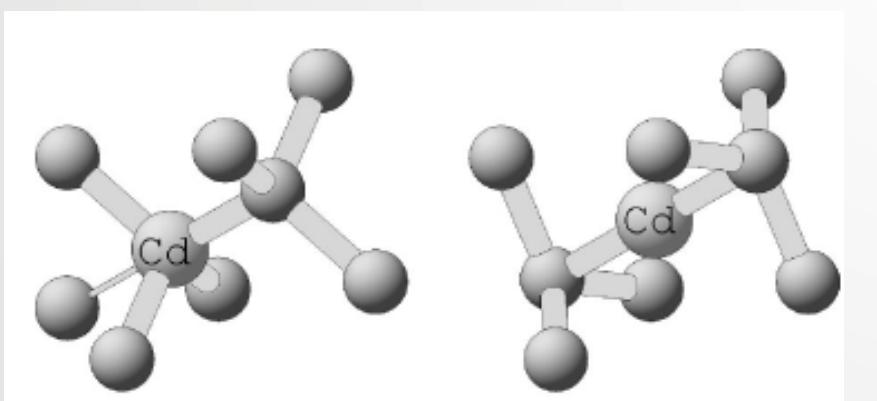
Figure 1. The Sn-split-vacancy configuration (left) and the substitutional Sn-vacancy configuration (right).
(*) Höhler et al., PRB 71, 035212 (2005)

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- 3) Cd-interstitial-complex → Cd takes BC-site & 2 Ge-atoms shift away from S-site (**)



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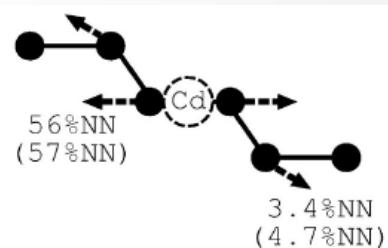


FIG. 6. The Cd-self-interstitial complex with Cd on the substitutional site (above left) leads after relaxation to the symmetrical complex with Cd on the bond center and the two host atoms shifted half way between the substitutional and interstitial positions (above right). The lower figure gives the calculated displacements of the neighbors from the ideal positions in percent of the nearest-neighbor distance for the Ge host. In brackets the results of the PPW calculation are given.

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Höhler et al. (Jülich)	Coutinho et al. (Aveiro)
1) Al, P, Ga, As, Se occupy S-position and V stays on a nn-S-position	1) Same findings
2) Cd, In, Sn, Sb, Bi move to the BC site with V 'split' between 2 S-sites	2) No theorital evidence for BC-site for heavier impurities
3) Cd-interstitial-complex → Cd takes BC-site & 2 Ge-atoms shift away from S-site	3) No calculations

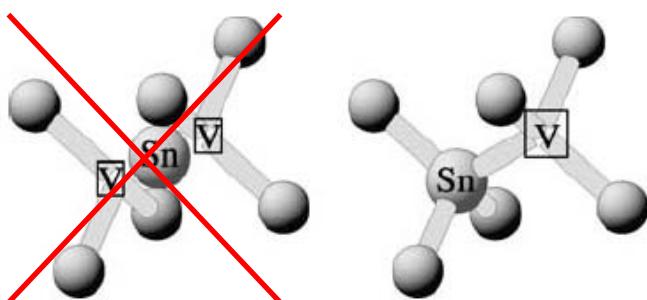
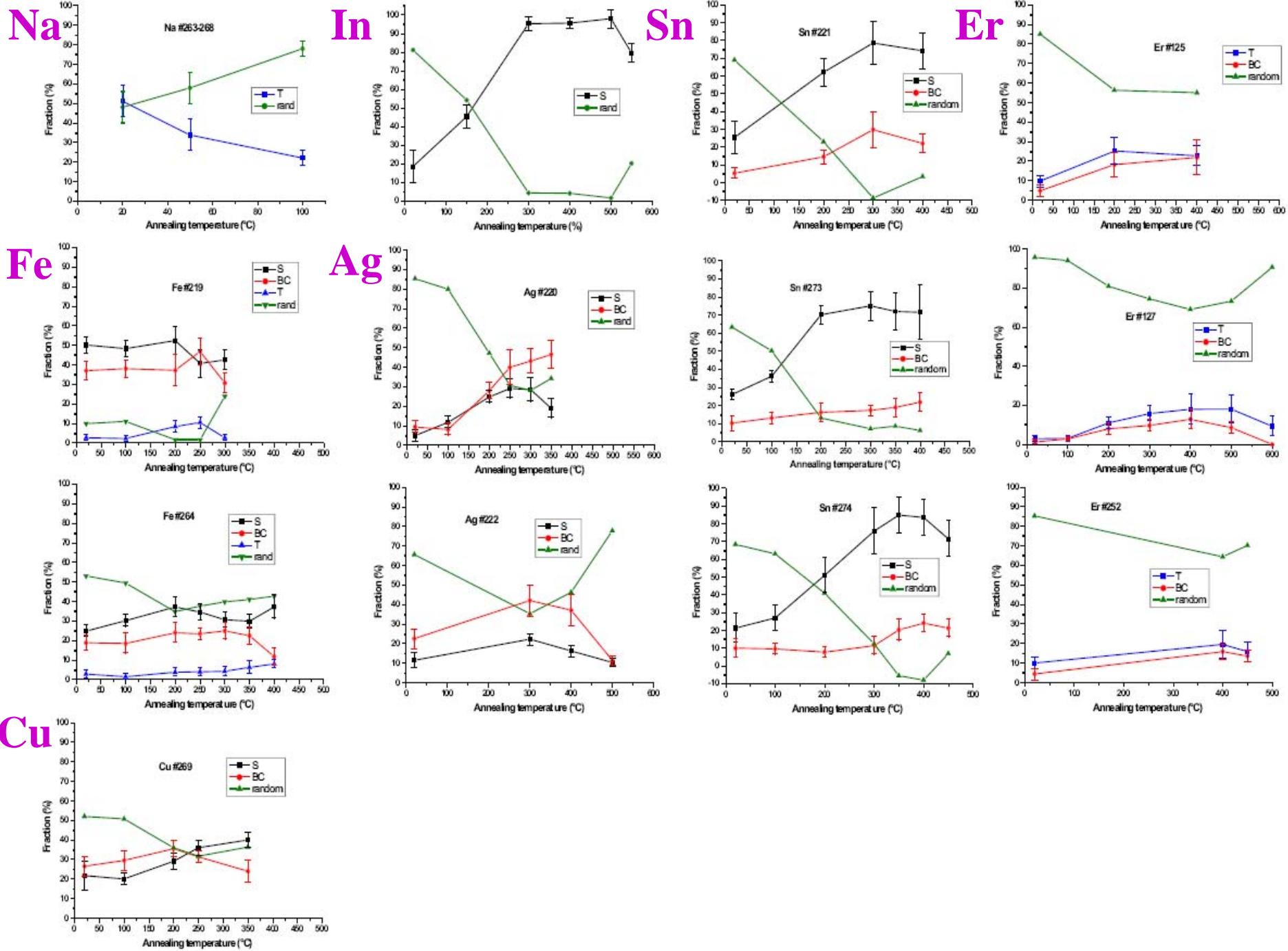


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Conclusions

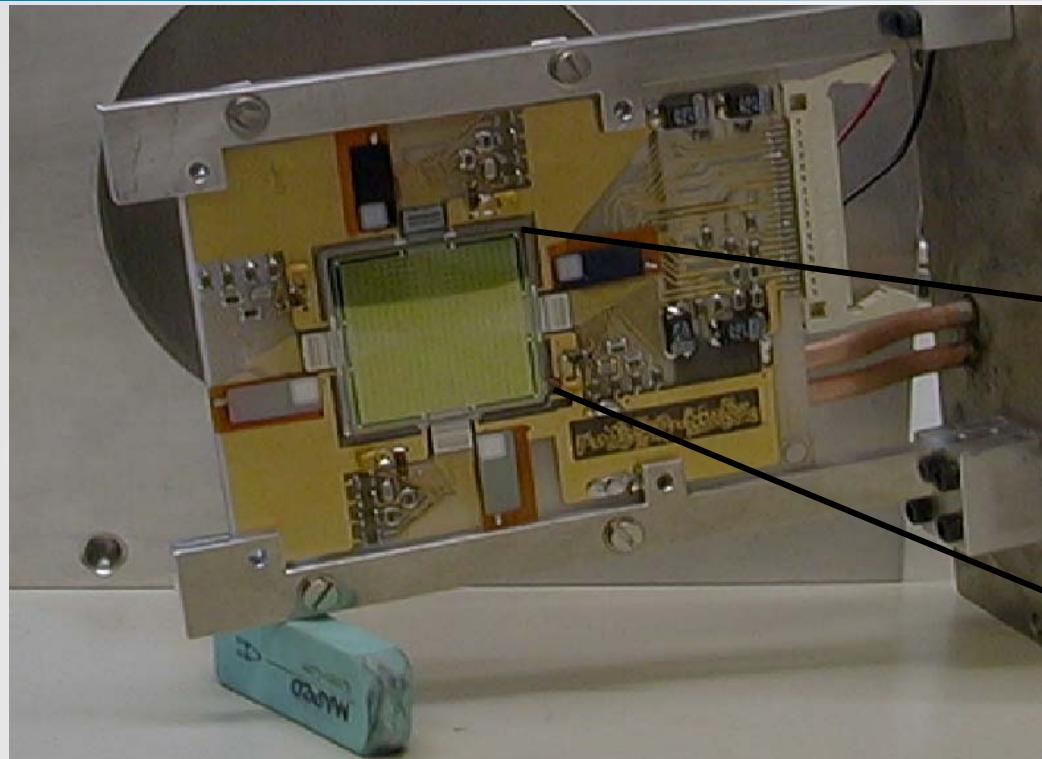
Lattice location of implanted ions in Ge

- « The lattice location of a number of impurities in Ge have been determined: Na, Fe, Cu, In, Ag, Sn and Er.
- « Very heavy (Er) and very low (Na) mass impurities do not occupy S-site but prefer the T-site.
- « All the intermediate mass impurities (Fe → Sn) occupy (at least partly) the S-site.
- « We find strong evidence of impurities occupying the bond-centered (BC) site. From theoretical calculations, this site can be connected to impurity-vacancy or impurity-interstitial complexes.
- « Annealing >100°C starts to remove lattice damage → could be linked with dissociating V₂-defect?

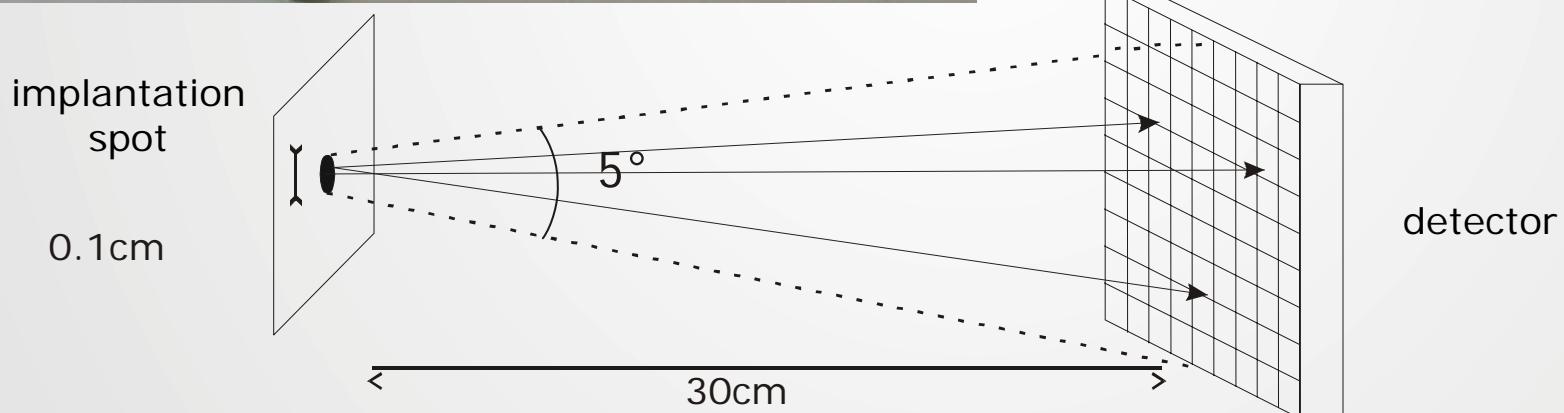
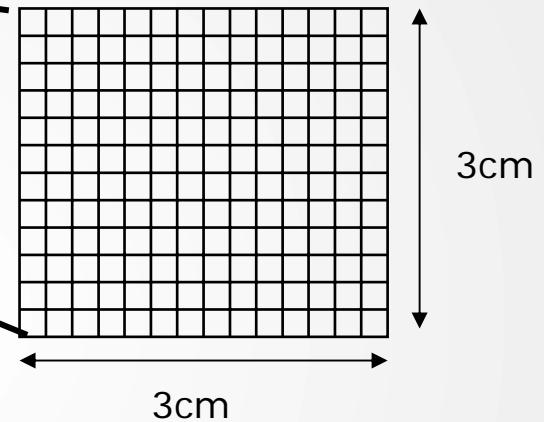
Thank you for your attention

Emission Channeling

Lattice location of implanted ions in Ge



Position Sensitive
Detector (PSD):
➤ $22 \times 22 = 484$ pixels
➤ energy sensitive

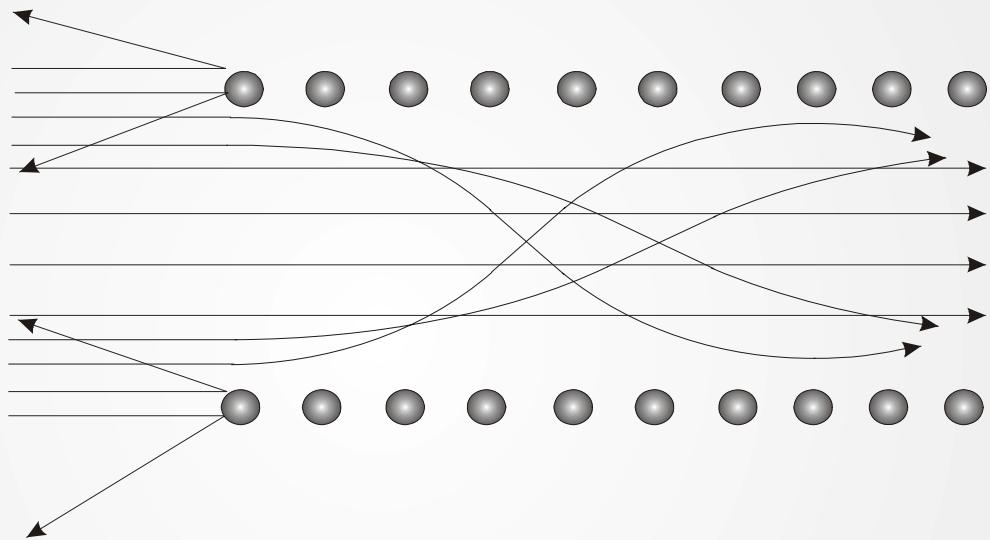


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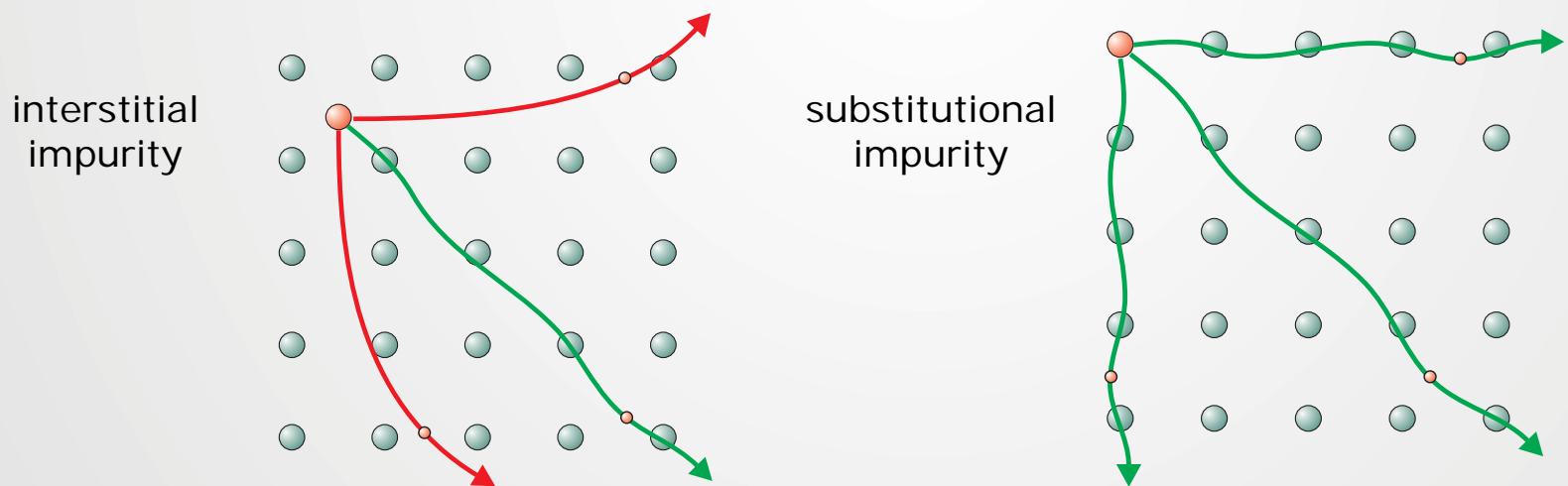
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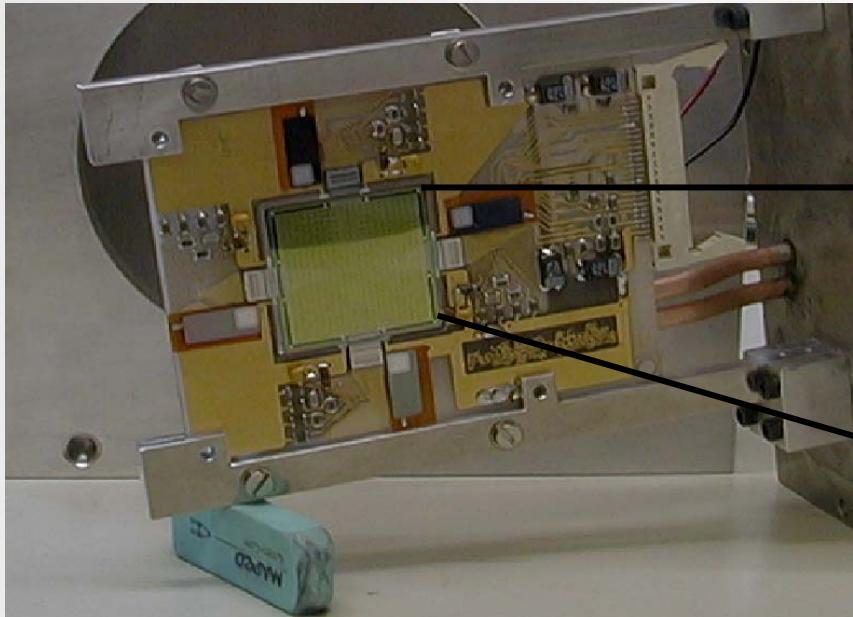
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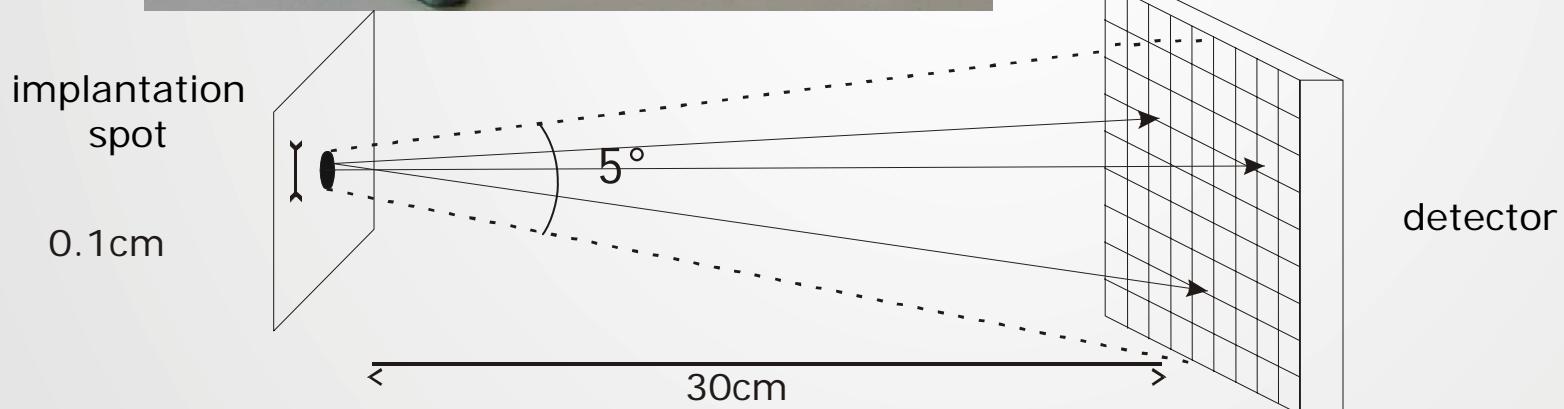
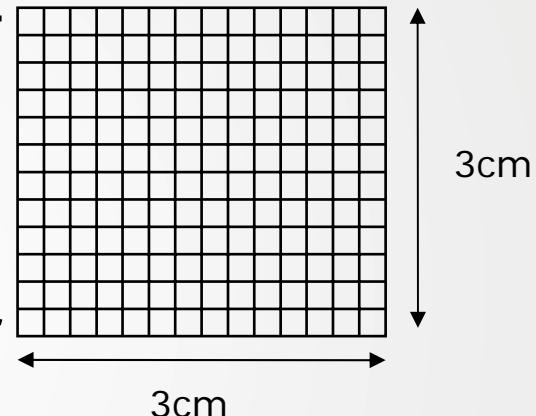
Emission Channeling

Lattice location of implanted ions in Ge

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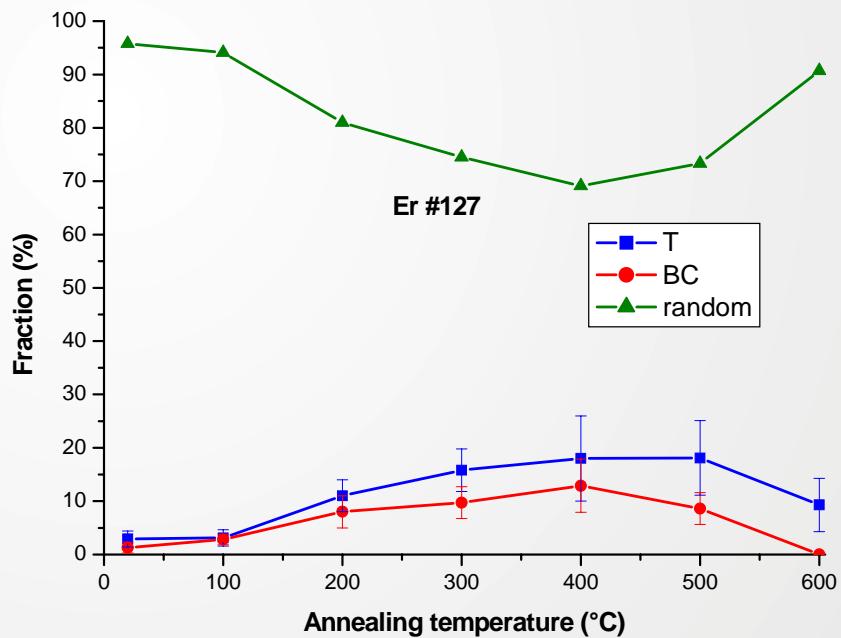
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Experimental results

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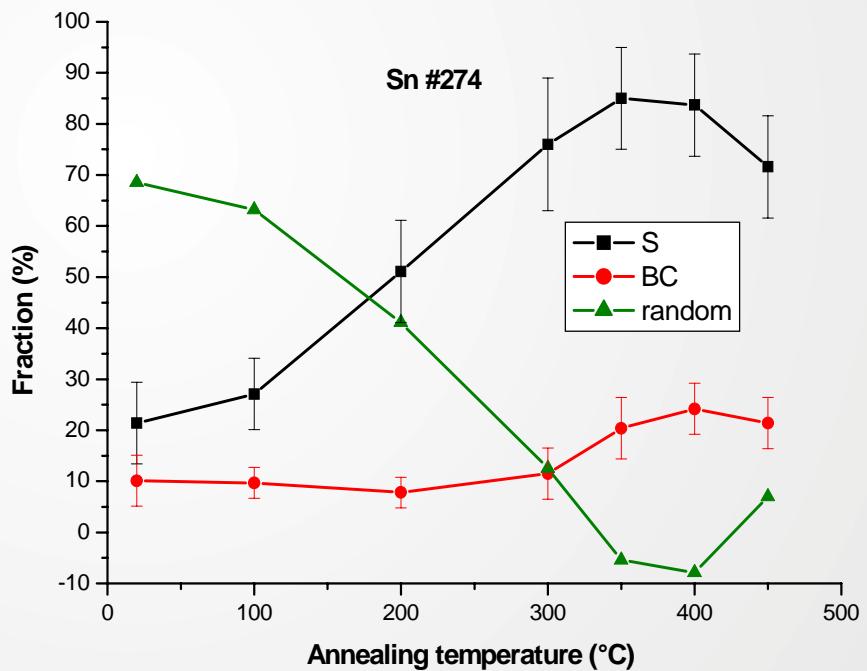
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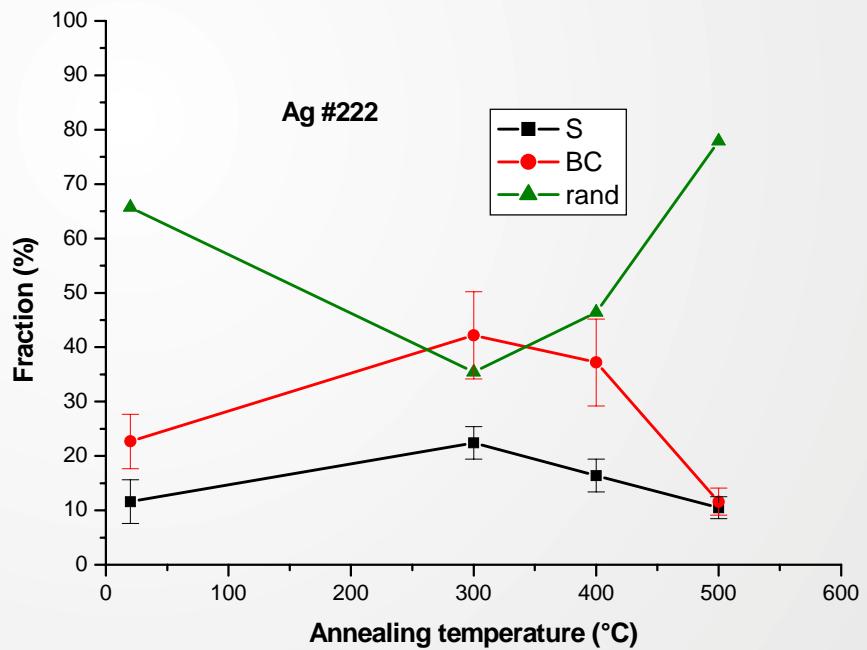
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 → removal of lattice damage after annealing @ 350°C



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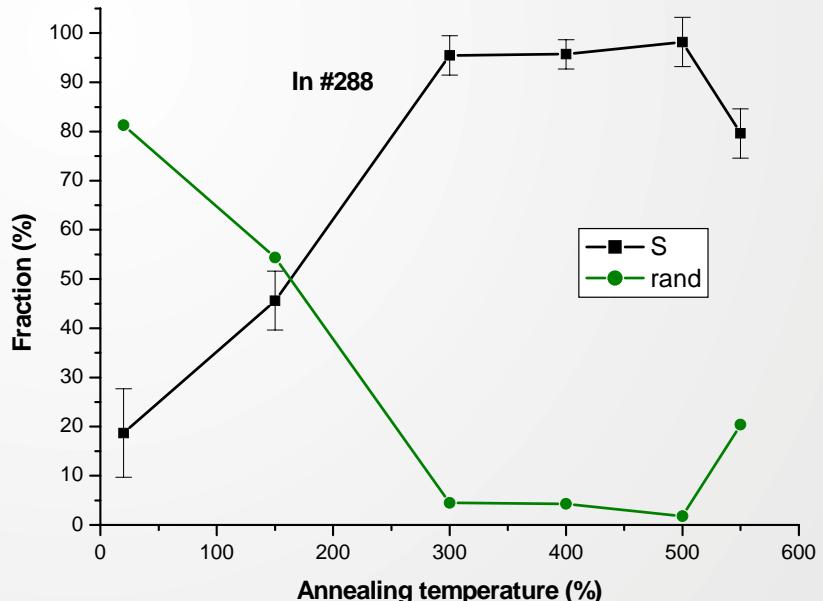
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 → same findings from very old RBS/C measurements (*)

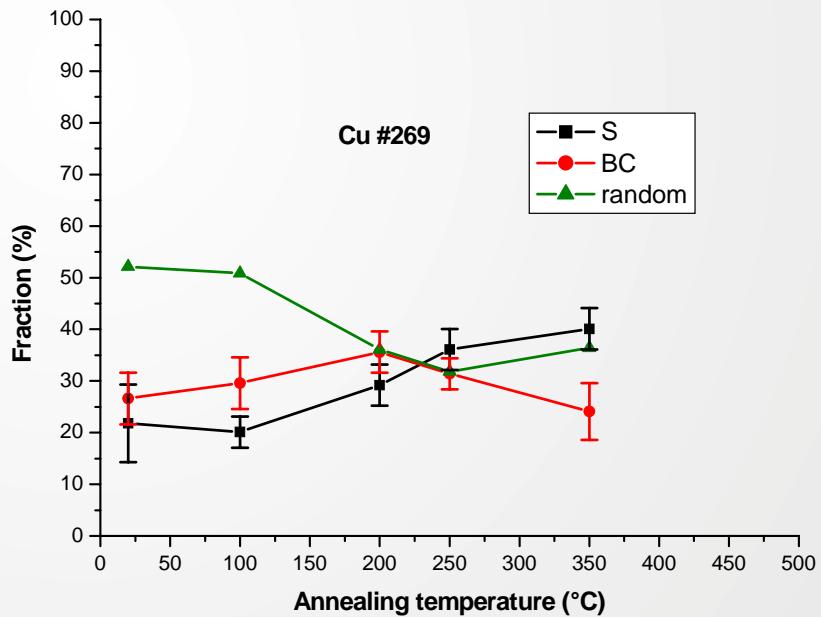


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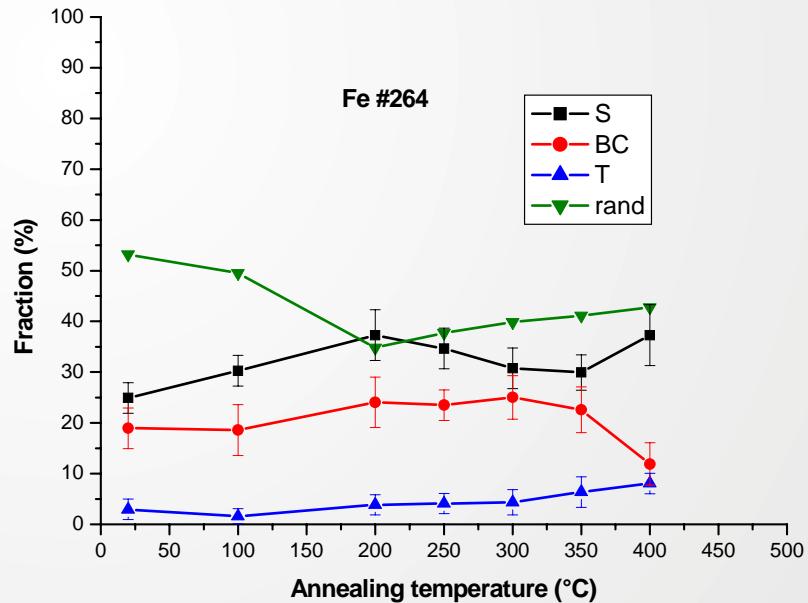
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→ small fraction (0-10%)
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→ small fraction (0-10%)
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- « Na → only consistent fits with Na on T-site
No detectable fraction on S...
→ 50% T at RT,
down to 20% at 100°C = diffusion?

