Advanced Strategies for Junction Formation in Germanium

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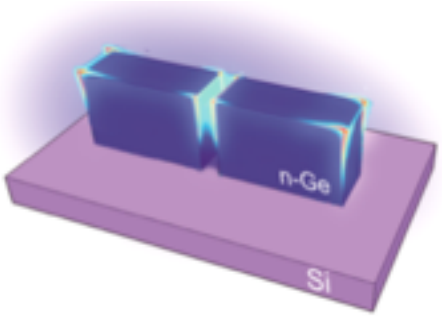
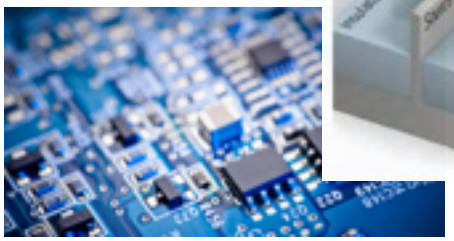
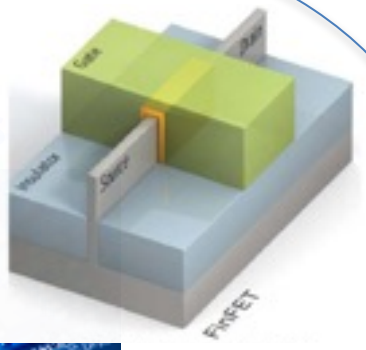
Ge devices



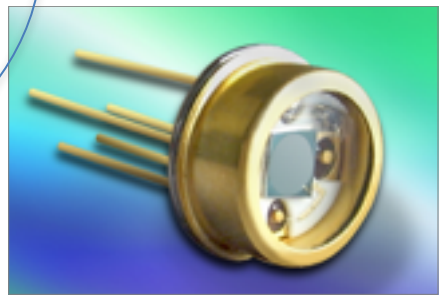
Plasmonic molecular sensors

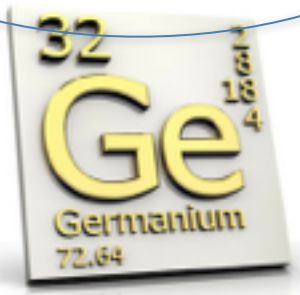
Nanolectronics

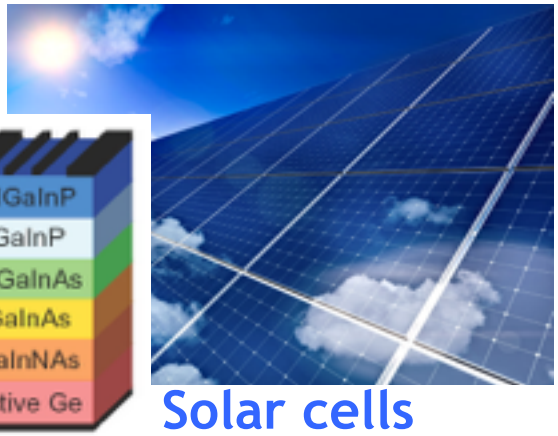




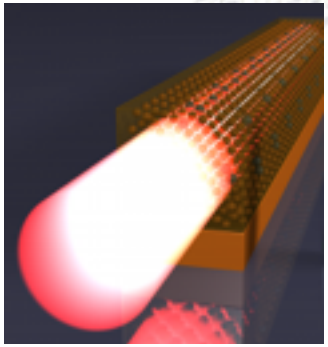
Photodetectors





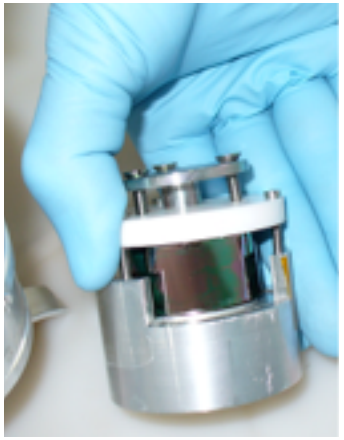


Solar cells



Lasers

γ-Ray detectors

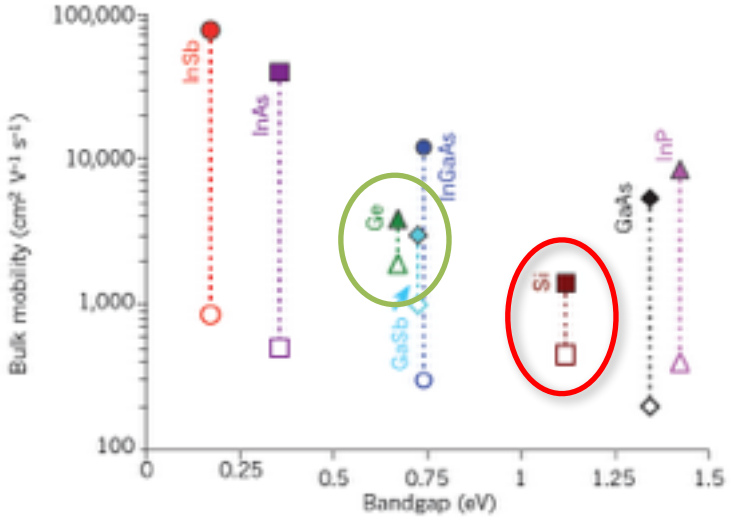


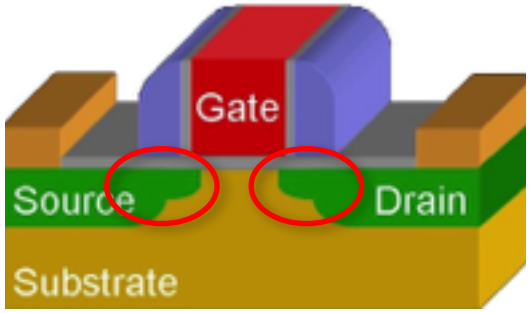
Outline

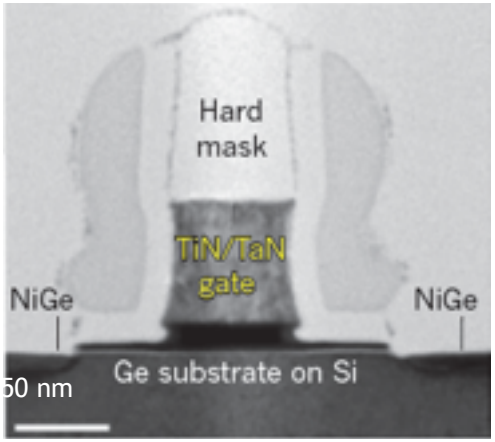
- Introduction
  - Motivations
  - Equilibrium diffusion mechanisms
  - Point defect engineering
- Diffusion under H irradiation
- Oxygen co-implantation
- Pre-amorphisation approch
- Considerations about HPGe doping

Why Germanium? Why diffusion?

(R. Pillarisetty, Nature 2011)







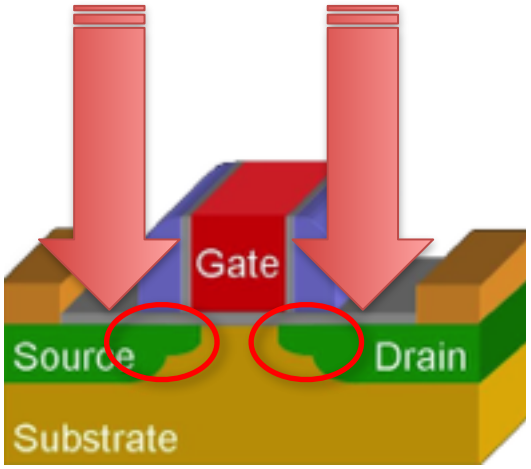
- e- and h+ higher mobility
- CHALLENGE for Ge implementation in devices: Shallow Source/Drain doping with High electrical activation (low Sheet Resistance).

Why Germanium? Why diffusion?

ION IMPLANTATION

+

ANNEALING



NEED for:

1. Deep understanding on dopant diffusion and activation phenomena during junction formation processing
2. Development of strategies for their control.

Recent Review Papers

JOURNAL OF APPLIED PHYSICS **113**, 031101 (2013)

APPLIED PHYSICS REVIEWS—FOCUSED REVIEW

Mechanisms of boron diffusion in silicon and germanium

S. Mirabella,[1,a)] D. De Salvador,[2] E. Napolitani,[2] E. Bruno,[1] and F. Priolo[1]
[1]*MATIS IMM-CNR and Dipartimento di Fisica e Astronomia, Università di Catania, Via Santa, Sofia 64, Catania I-95123, Italy*
[2]*MATIS IMM-CNR and Dipartimento di Fisica e Astronomia, Università di Padova, Via, Marzolo 8, Padova I-35131, Italy*

(Received 13 June 2012; accepted 25 September 2012; published online 16 January 2013)

APPLIED PHYSICS REVIEWS **1**, 011301 (2014)

APPLIED PHYSICS REVIEWS

Diffusion of *n*-type dopants in germanium

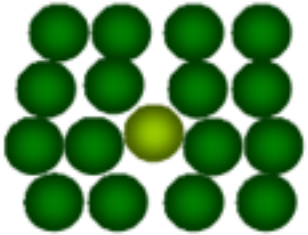
A. Chroneos[1,2,a)] and H. Bracht[3,b)]
[1]*Engineering and Innovation, The Open University, Milton Keynes MK7 6AA, United Kingdom*
[2]*Department of Materials, Imperial College, London SW7 2AZ, United Kingdom*
[3]*Institute of Materials Physics, University of Münster, Wilhelm-Klemm-Strasse 10, D-48149 Münster, Germany*

Point defects - diffusion

V

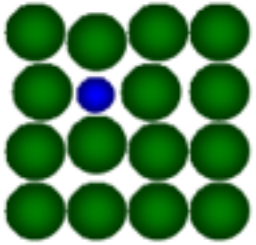
Vacancy

I



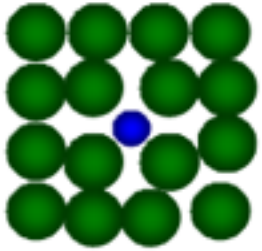
Self-interstitial

A_s



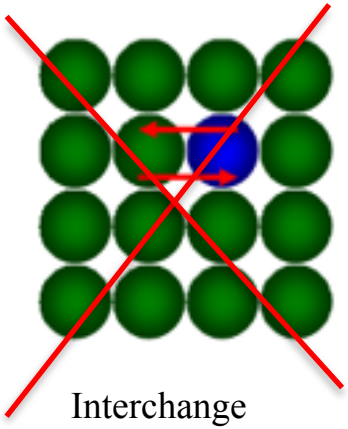
Substitution impurity

AI

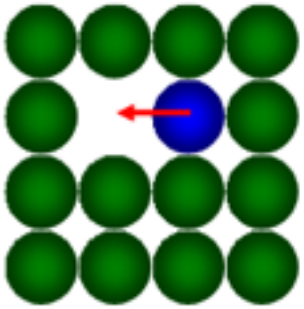


Interstitial impurity

$$A_s + V \Leftrightarrow AV_{mobile}$$



Interchange



Point defect mediated diffusion

Equilibrium Diffusion in Ge

- Ge self diffusion (E_{self}=3.13 eV) is dominated by vacancies, V^{2-} or V^0 under n- or p-type doping respectively *(see A. Chroneos and H. Bracht APR 2014 and refs. therein)*
- N-type dopants: $E_{n\text{-}type} < E_{self}$

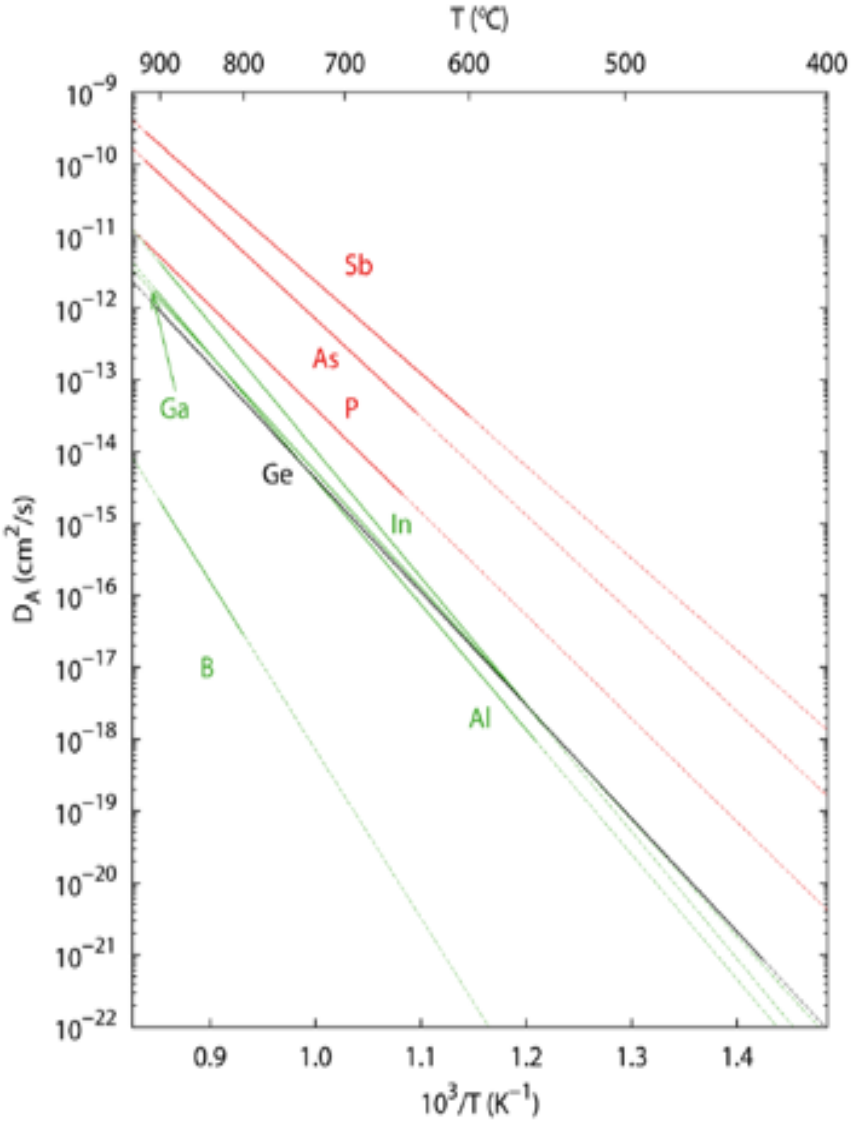
$$A_s^+ + V^{2-} \Leftrightarrow AV^-_{mobile}$$

- P-type dopants: $E_{p\text{-}type} \approx E_{self}$

$$A_s^- + V^0 \Leftrightarrow AV^-_{mobile}$$

- Boron: $E_B > E_{self}$ *(see S. Mirabella et al. APR 2013, A. Chroneos and H. Bracht APR 2013 and refs. therein)*

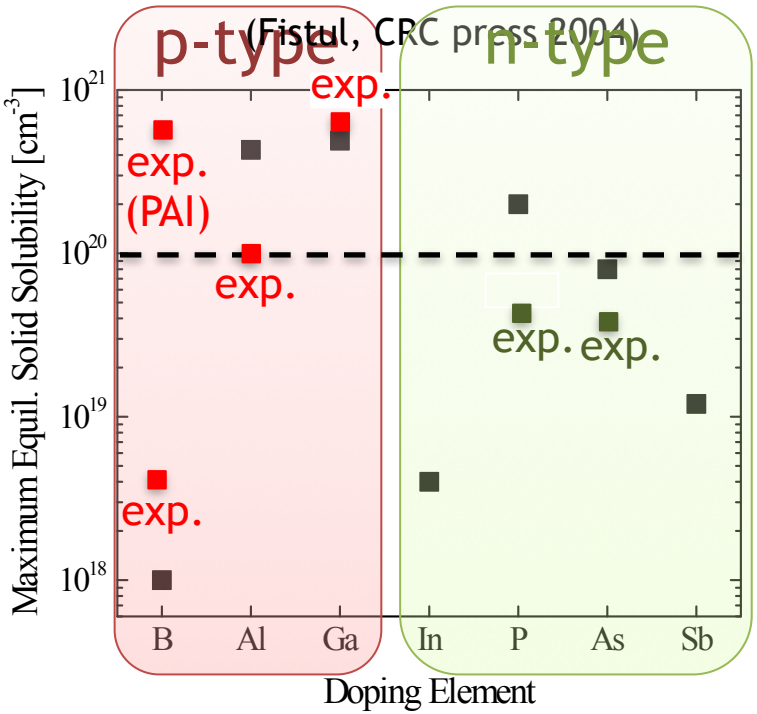
$$B_s + I \Leftrightarrow BI_{mobile}$$



(A. Chroneos and H. Bracht APR 2014)

Solubility

Calculated Solubilities in Ge



Experimental maximum values with ion implantation or diffusion sources after conventional thermal annealings

Role of defects. Main dopant-defect reactions

- Diffusion:

$$I + V \Leftrightarrow 0$$

$$A_s + V \Leftrightarrow AV_{mobile} \quad \text{(P, As, Sb, Al, Ga, In)}$$

$$A_s + I \Leftrightarrow AI_{mobile} \quad \text{(B)}$$

- Clustering (deactivation):

$$AX_{(mobile)} + A_s \Leftrightarrow A_2X_{(immobile)}$$

$$AX_{(mobile)} + X \Leftrightarrow AX_{2\,(immobile)}$$

$$AX_{(mobile)} + T \Leftrightarrow AXT_{(immobile)}$$

$X = I$ or V

T=defect and/or impurity trap

Point defect engineering

- Diffusion:

$$I + V \Leftrightarrow 0$$

$$A_s + V \Leftrightarrow AV_{mobile} \quad \text{(P, As, Sb, Al, Ga, In)}$$

$$A_s + I \Leftrightarrow AI_{mobile} \quad \text{(B)}$$

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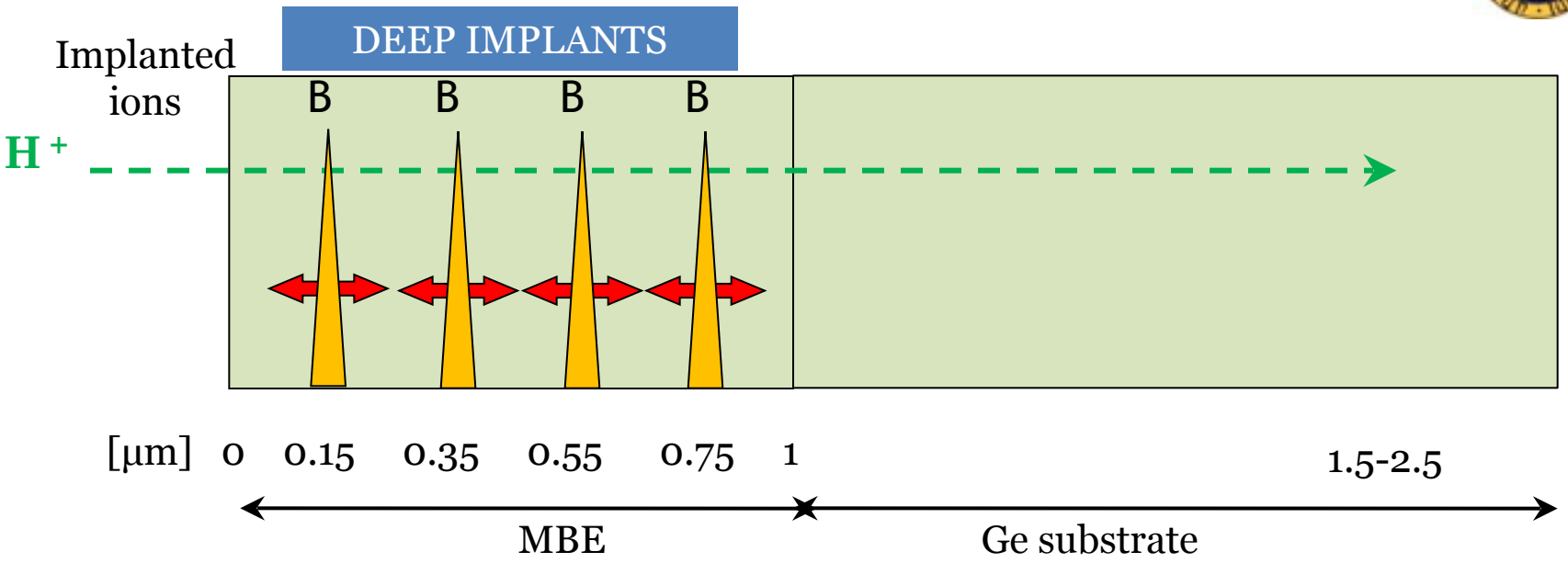
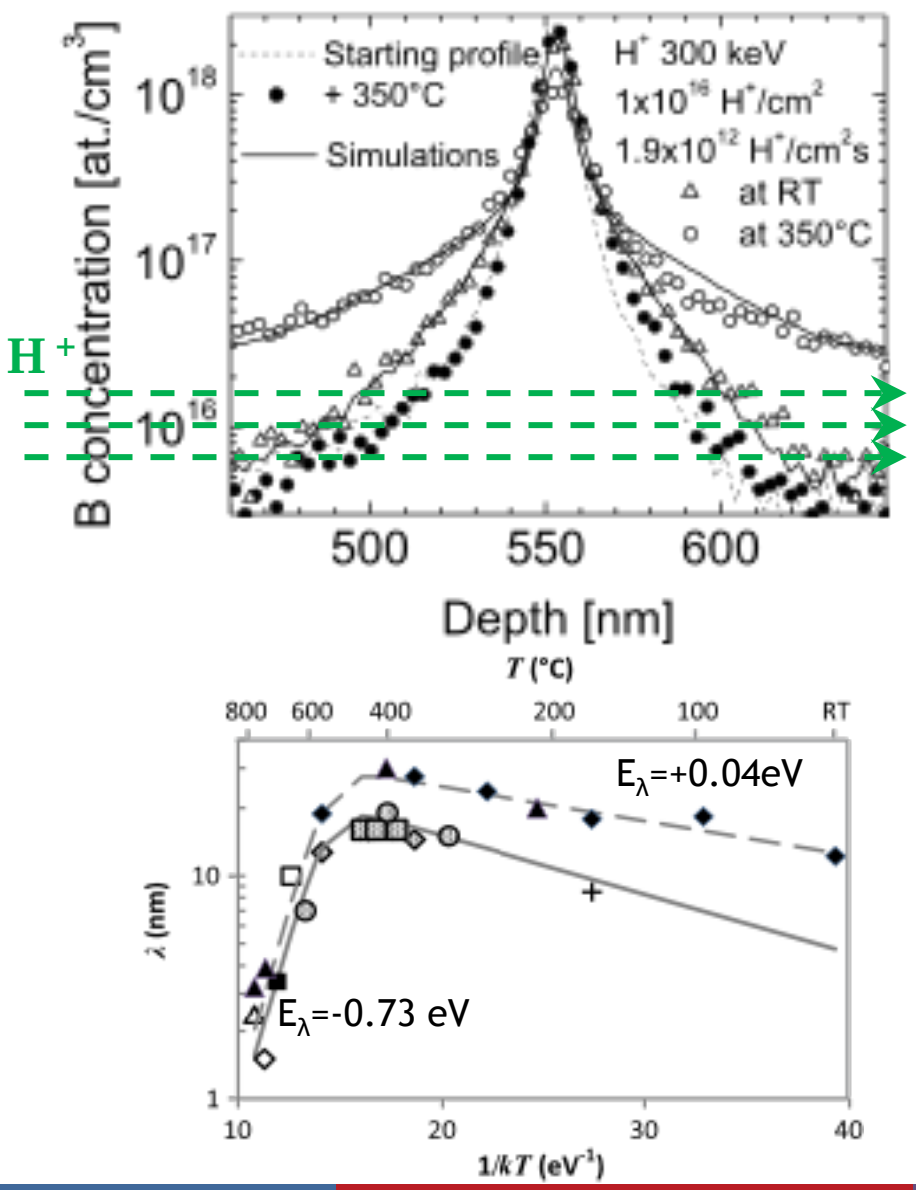
Radiation enhanced diffusion

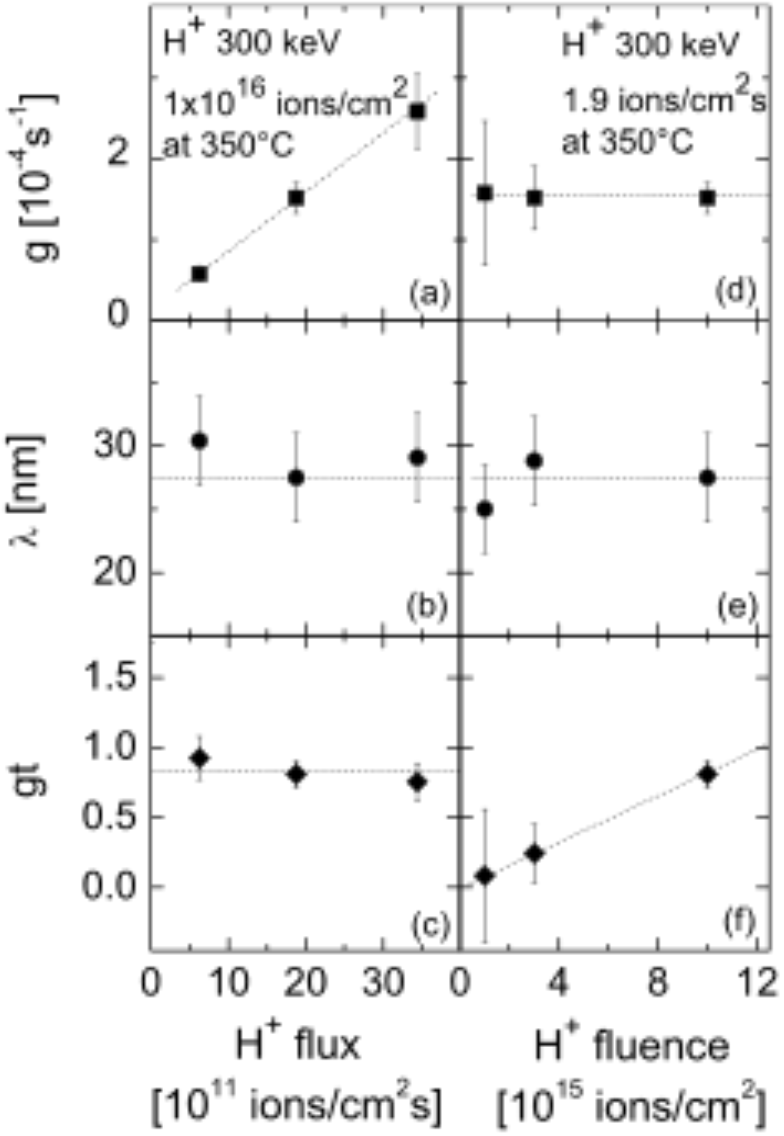


- Deep ion irradiation generates dilute I-V Frenkel pairs.
- B deltas through its diffusion mechanism mediated by I's provide a powerful method to investigate self-interstitials

Radiation Enhanced Diffusion

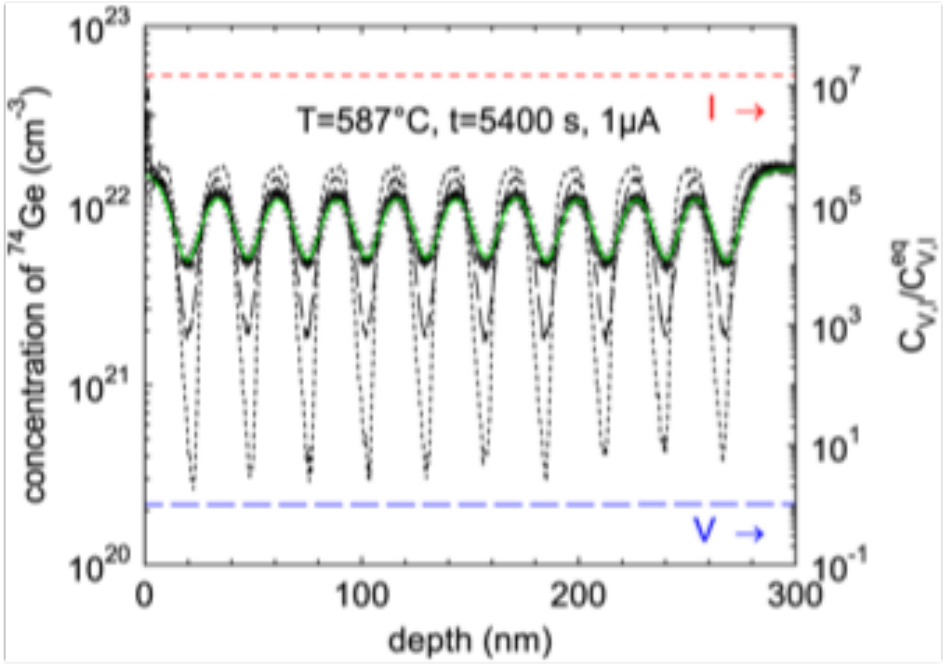
(E. Bruno et al. PRB 2009)

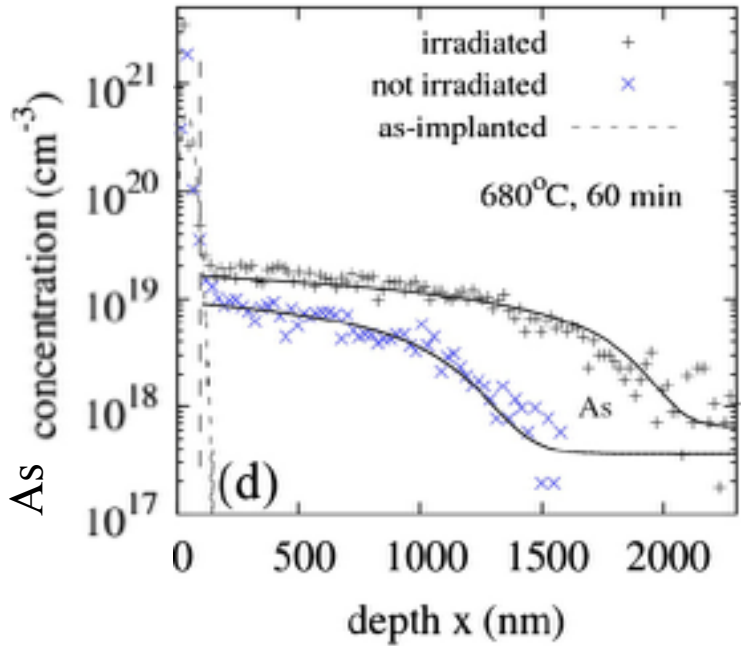




Self and donor diffusion under RED

(H. Bracht et al. PRL 2009, S. Schneider et al. APL 2011 and PRB 2013)

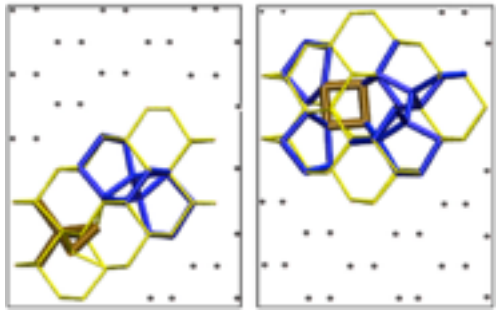


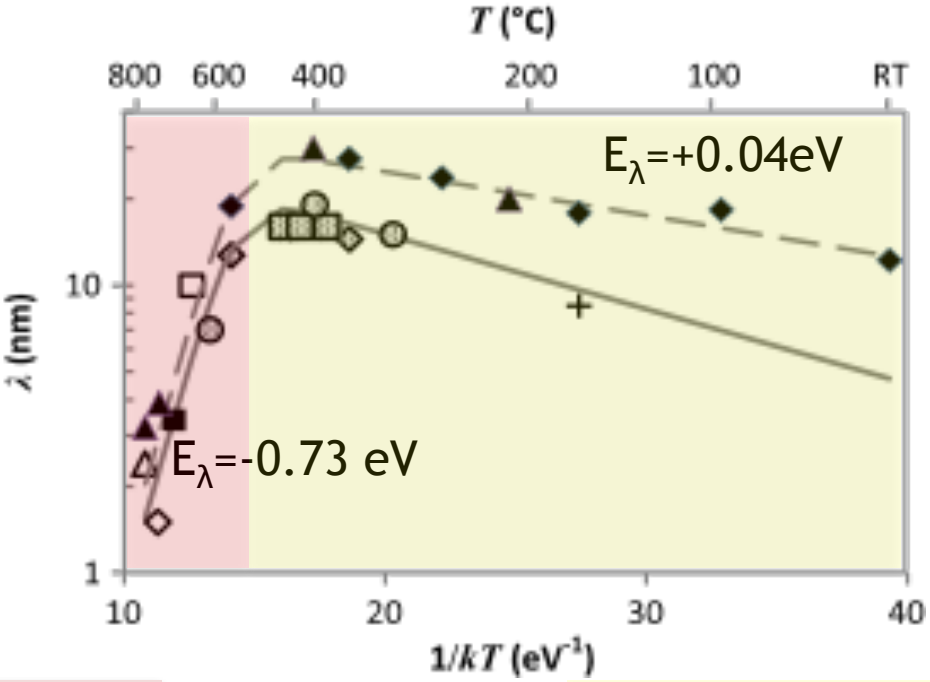


- Self-diffusion measured by isotopically enriched MBE Ge layers
- n-type dopant co-diffusion
- Full model based on differential equation of all species/ reactions involved
- RED enhances self-diffusion and B diffusion, while donor diffusion is less affected

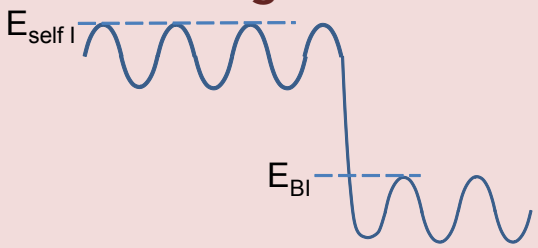
I-morph

(N.E.B. Cowern et al. PRL 2013)





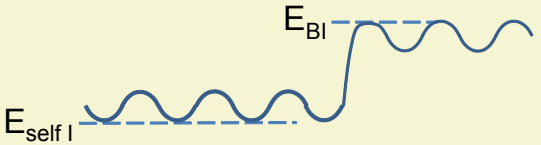
High T



I-morph
$S_{I\text{-}morph}$≈30k
$E_{I\text{-}morph}$=6.1 eV

BI
S_{BI}≈20k
E_{BI}=4.65 eV

Low T



I compact
S_I≈7k
E_I=4.57 eV

BI
S_{BI}≈20k
E_{BI}=4.65 eV

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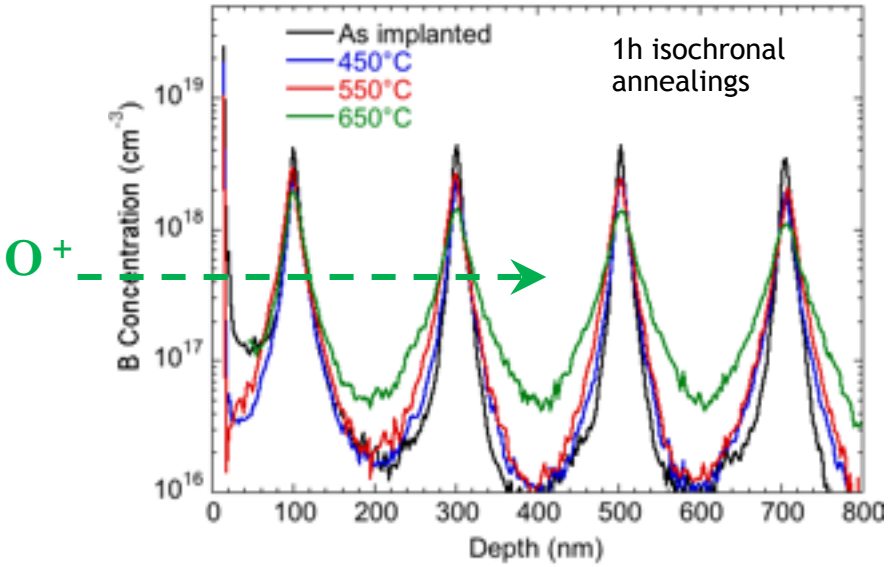
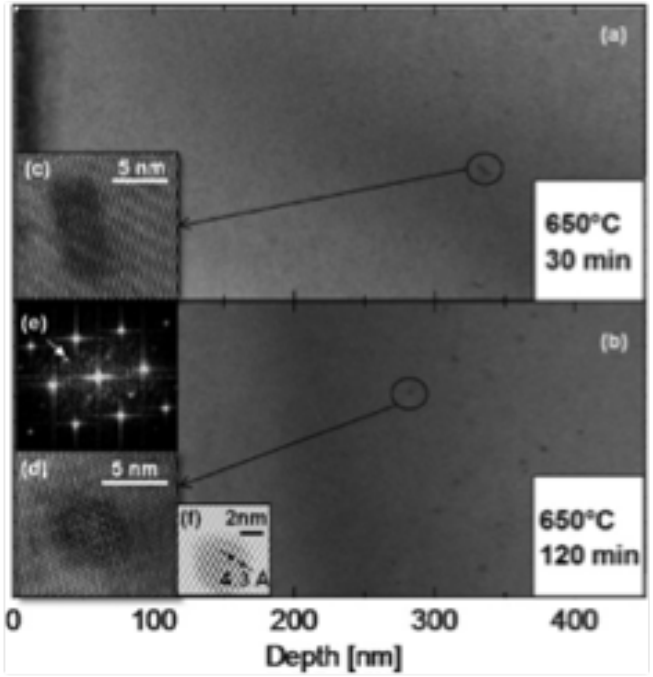
GeO_2 nanoclusters

(Scapellato et al. PRB 2011)



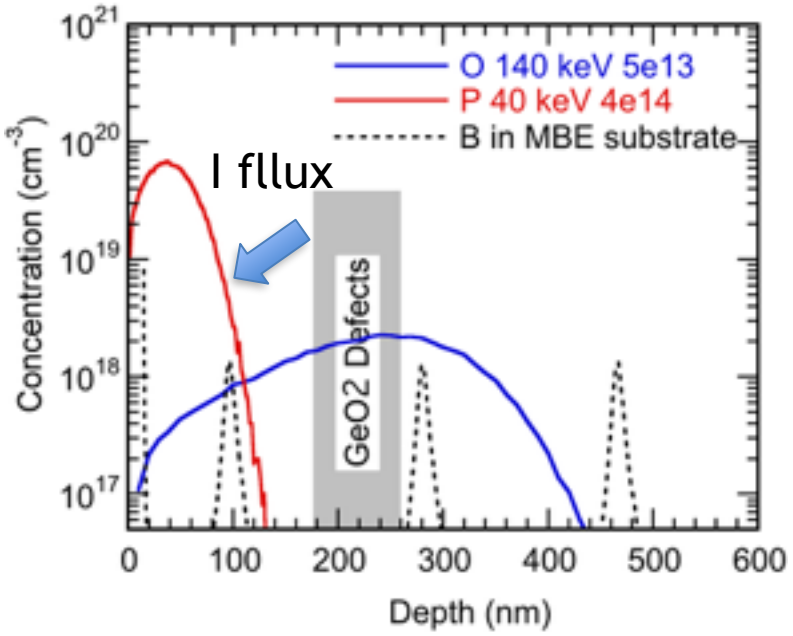


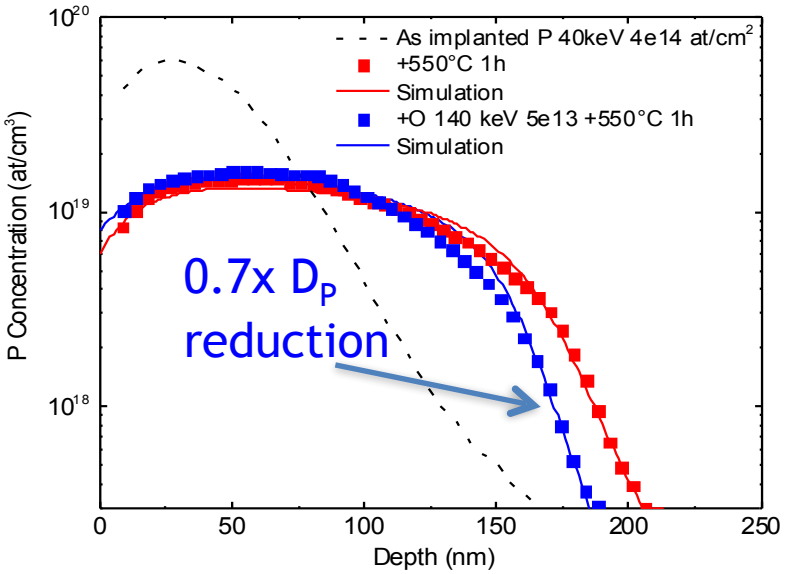
$$I + V \Leftrightarrow 0$$

$$I \uparrow \Rightarrow V \downarrow$$

I's injection related to the formation and shape transformation of GeO_2 nanoclusters.

O+P implantation





$$I + V \Leftrightarrow \varnothing$$

$$P_s^+ + V^{2-} \Leftrightarrow PV^-_{mobile}$$

$$PV^-_{mobile} + P_s^+ \Leftrightarrow P_2V^-_{immobile}$$

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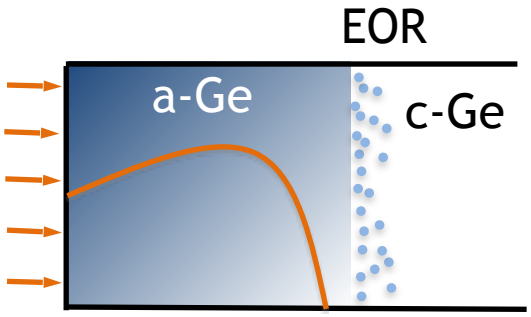
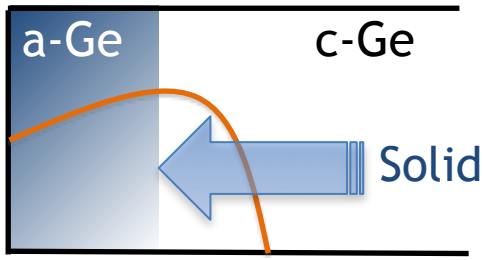
- Persepctives for HPGe doping

Amorphisation/regrowth approach

High dose dopant Implantation or Ge amorphising implants



Thermal annealing

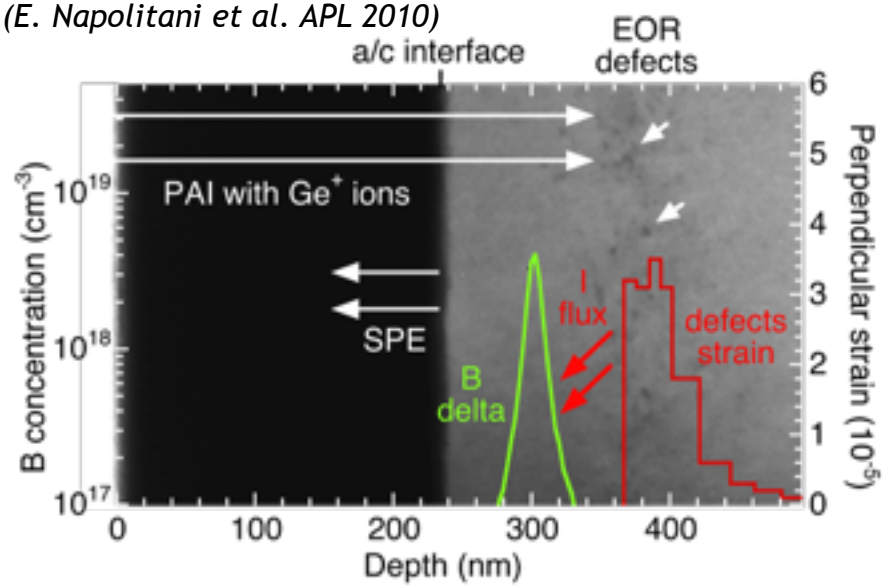


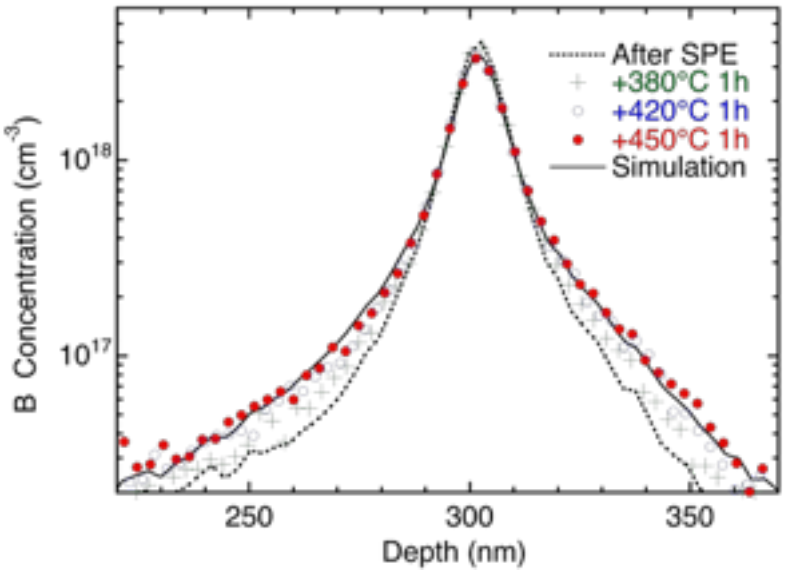
Phase Transition

- Highly non equilibrium process
- Dopant incorporation influneced by interface mechanisms
- I injection from inner defects (EOR)
- SPE can be done at low temperatures (T=3-400°C)

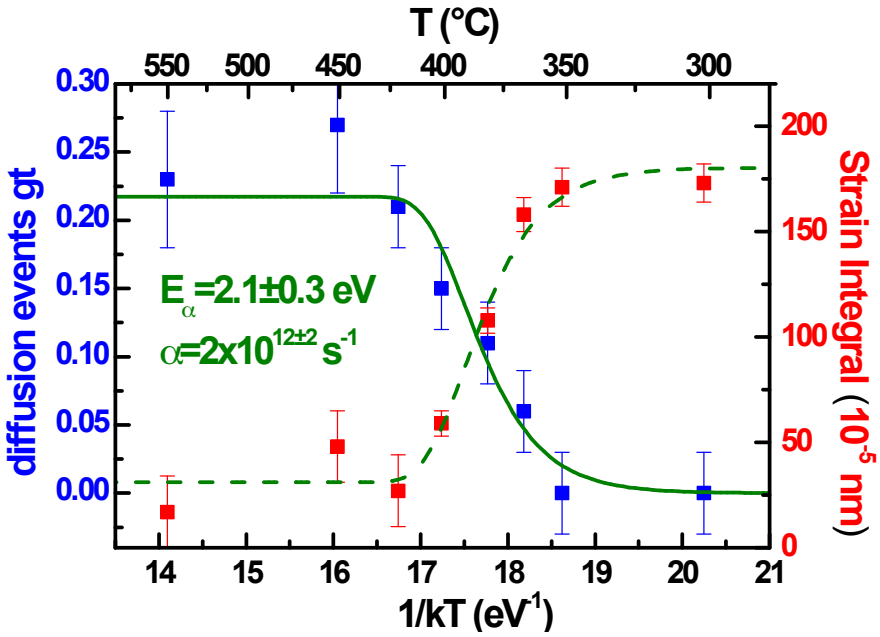
PAI and End-Of-Range defects

(E. Napolitani et al. APL 2010)



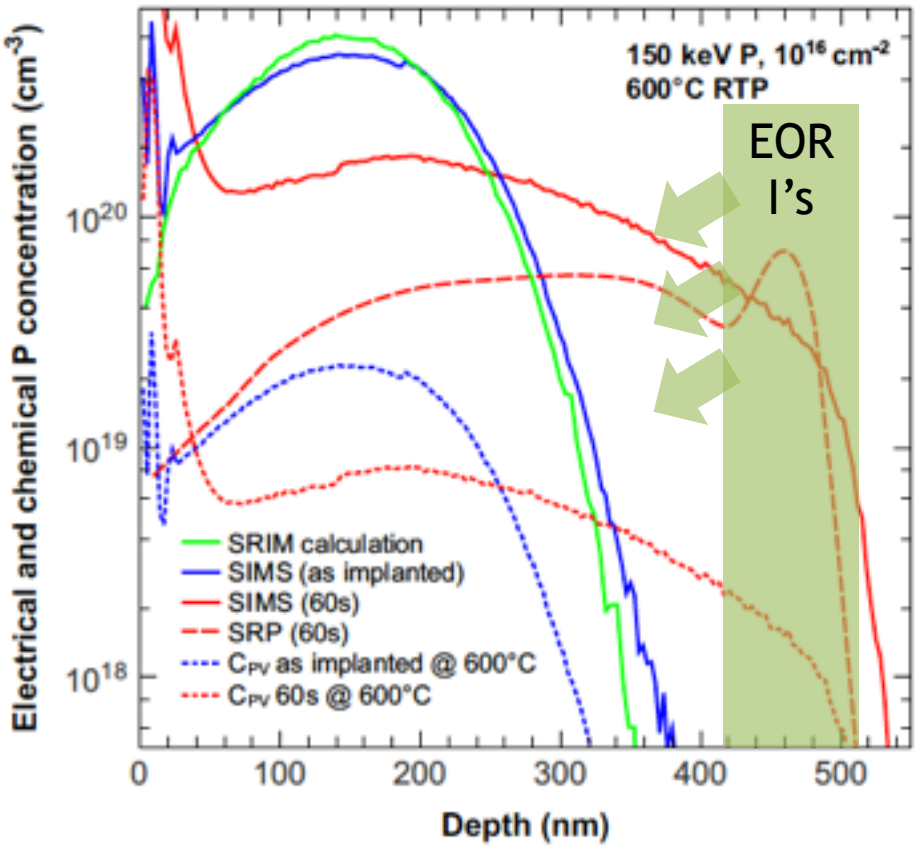


- After Preamorphization and Solid Phase Epitaxy, End-Of-Range defects form inducing positive strain, i.e. are formed by I's
- After annealing EOR defects dissolve with a Ea=2.1 eV injecting I's.
- This is a further direct evidence of I-mediated mechanism of B diffusion



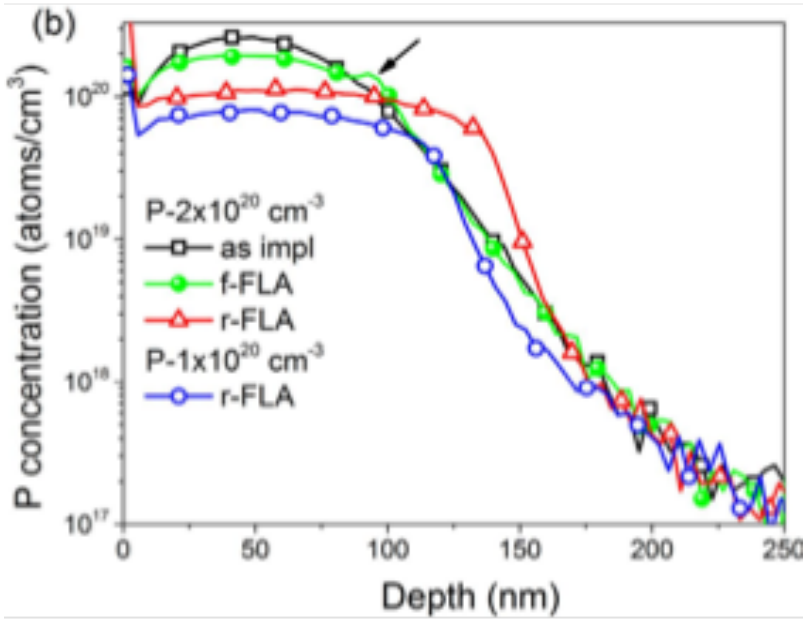
Electrical activation and EOR dissolution

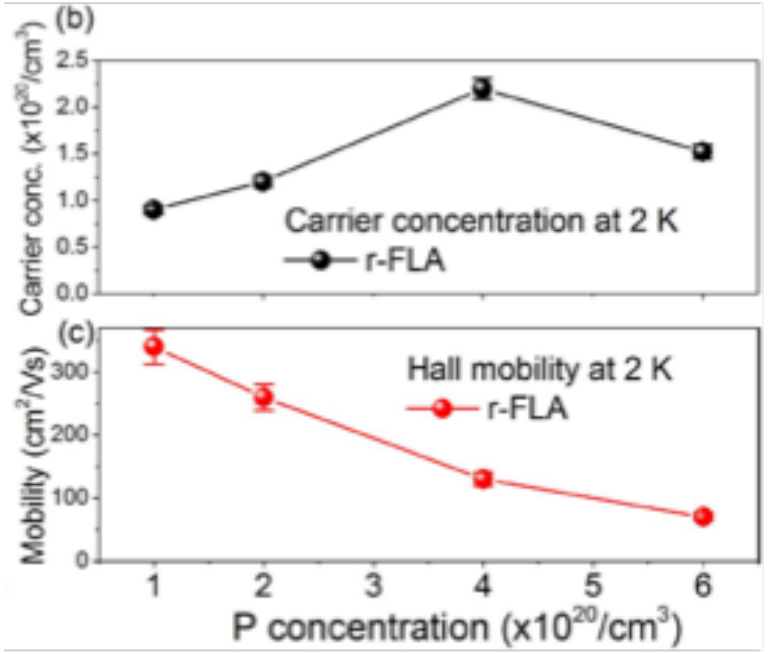
(J. Vanhellemont and E. Simoen, Mat. Sci. In Semicond. Proc. 2012)



Flash lamp ms-annealing

Very high activation bringing the system very out from equilbrium





Prucnal, S. et al. Sci. Rep. 6, 27643; doi: 10.1038/srep27643 (2016)

Summary

- We show possible methods to increase activation related with an increase of C_I:
  - Irradiation at high T (not much effective)
  - Significant injection of I's can be induced by O clustering.
- Amorphising ion implantation + annealing looks very effective
  - EOR injects interstitial
  - Very high activation is demonstrated under fast annealing conditions

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Relevant diffuser fo HP-Ge processes

- Cu: dissociative process

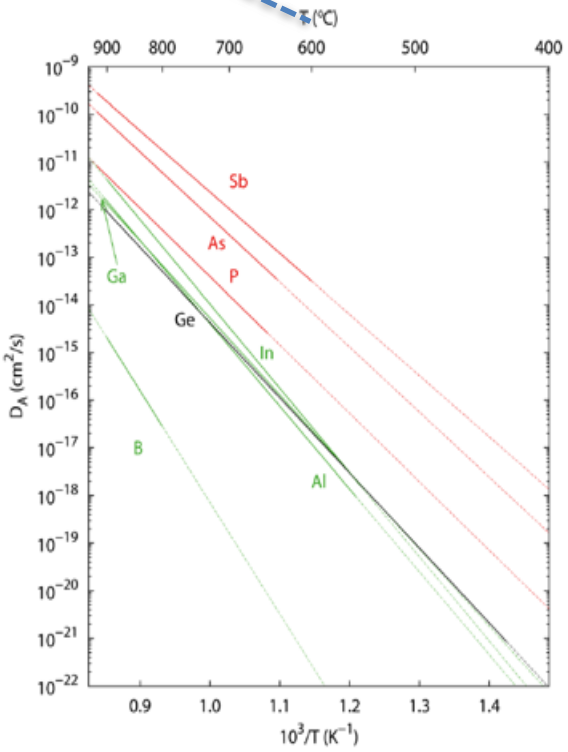
$$Cu_s^- \Leftrightarrow CuI^+_{mobile} + V^{-2}$$

  - P-Doping metal contaminant
  - Less vacancy more diffusion

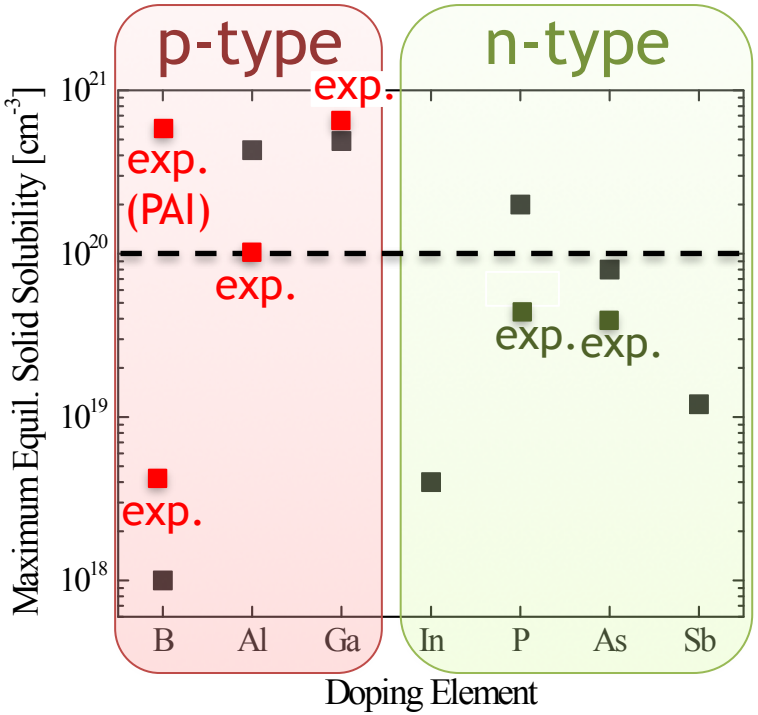
- Lithium:

$$Li_s^+ \Leftrightarrow LiI^+_{mobile} + V^0 \quad (???)$$

  - Low temperature diffuser
  - It diffuse too much (diffusion length of mm order but 100nm is enough)



Activation for HPGE



Gap shrinks, no great advantage for barrier action

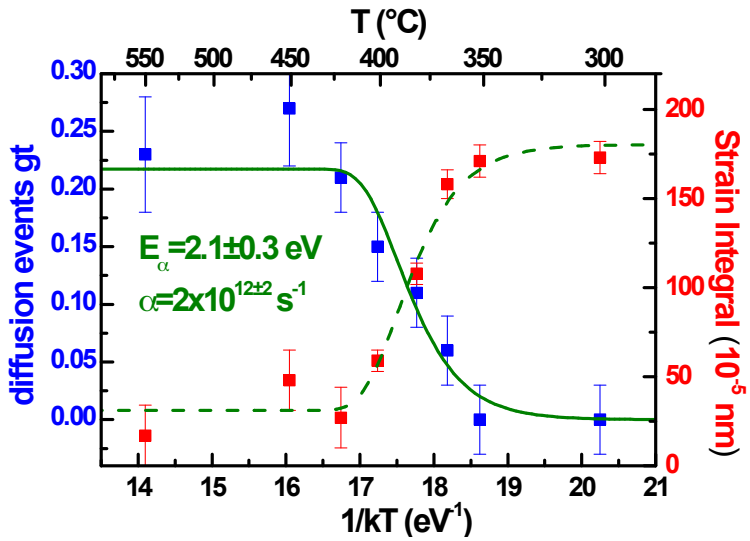
Activation level for HPGe processes

HPGe doping issiues

- Activation and junction depth are not so critical
- Large area and possibly low costs
- Metal contamination of high purity Ge is a main issues:
  - High purity processes
  - Low temperature processes

Doping possibilities

- Equilibrium diffusion of standrad dopants can meet junction depth and activation requirements. (SOD of P next talk)
  - Low cost
  - Large area
  - Short junction depth (easy to segment)
  - but relatively high termal budget....
- PAI coud be considered with a specific R&D.



Acnowledgments

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