P implantation into pre-amorphized germanium and subsequent annealing: Solid phase epitaxial regrowth, P diffusion and activation

related publication:

Posselt, M., Schmidt, B., Anwand, W., Grötzschel, R., Heera, V., Wündisch, C., Skorupa, W., Hortenbach, H., Gennaro, S., Bersani, M., Giubertoni, D., Möller, A., Bracht, H.
P implantation into pre-amorphized germanium and subsequent annealing: solid phase epitaxial regrowth, P diffusion and activation
Proc. Int. Workshop on INSIGHT in Semiconductor Device Fabrication, Metrology and Modeling (INSIGHT-2007), 06.-09.05.2007, Napa, USA, pp. 309-315

Introduction

renewed interest in Ge

carrier mobility is higher than in Si,

SiO_2 is increasingly replaced by high-k dielectrics

n and p doping by implantation and subsequent annealing

P, As **B**, Ga

high doping level → high implantation fluence

into crystalline Ge (amorphization by P, As, Ga implants)

into pre-amorphized Ge

this talk:

implantation of P *into preamorphized material*, subsequent RTA or FLA

focus on:

(i) formation of amorphous layers during Ge pre-amorphization implantation

(ii) regrowth of the amorphous layer by solid phase epitaxy (SPE)

(iii) P diffusion in amorphous Ge

(iv) P redistribution during SPE

(v) concentration-dependent P diffusion in single-crystalline Ge

(vi) activation of P

Experiments

(100) p-Ge with 10 nm SiO_2 cap layer

pre-amorphization implantation (PAI):

100, 150, 200, 300, 400 keV Ge, 1-1.2x10^{15} cm^{-2}

30 keV P implantation, 3x10^{15} cm^{-2}

RTA (N_2): 60 s at 400, 500, 600 ^{0}C

FLA (Ar): 240 s pre-heating at 400 ^{0}C (450 ^{0}C = mixed RTA+FLA),

3, 20 ms flash at 800 and 900 ^{0}C

Analysis

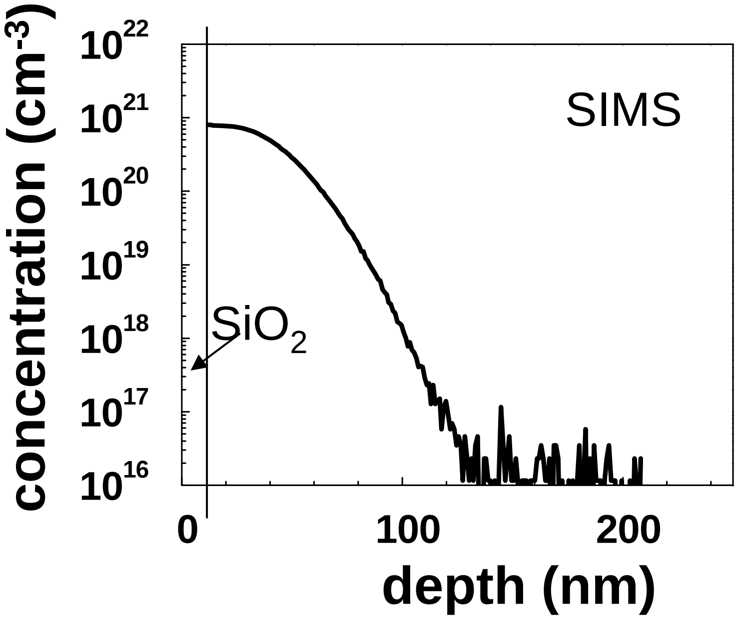
SIMS, RBS/C, SRP, Hall measurements

Results

(i) formation of amorphous layers during Ge pre-amorphization implantation

Ge PAI		thickness (nm)	
Energy (keV)	Fluence ($10^{15}cm^{-2}$)	RBS/C	Crystal-TRIM
100	1	105	90
150	1	150	135
200	1	177	175
300	1	254	260
400	1.2	322	350

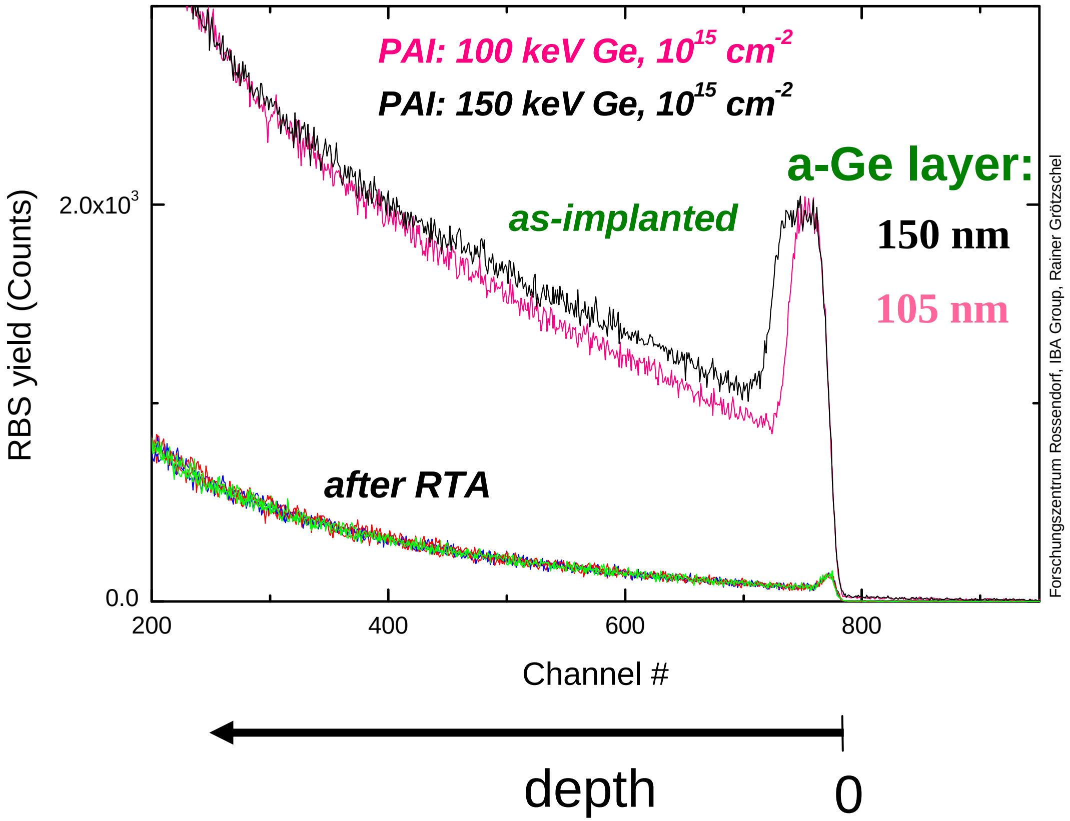
30 keV P, $3x10^{15}$ cm^{-2}



→ **as-implanted P profile fully embedded in a-Ge**

(ii) regrowth of the amorphous layer by solid phase epitaxy (SPE)

RBS/C damage and defect profiles



as-implanted

RTA (60 s):

400 ^{0}C

500 ^{0}C

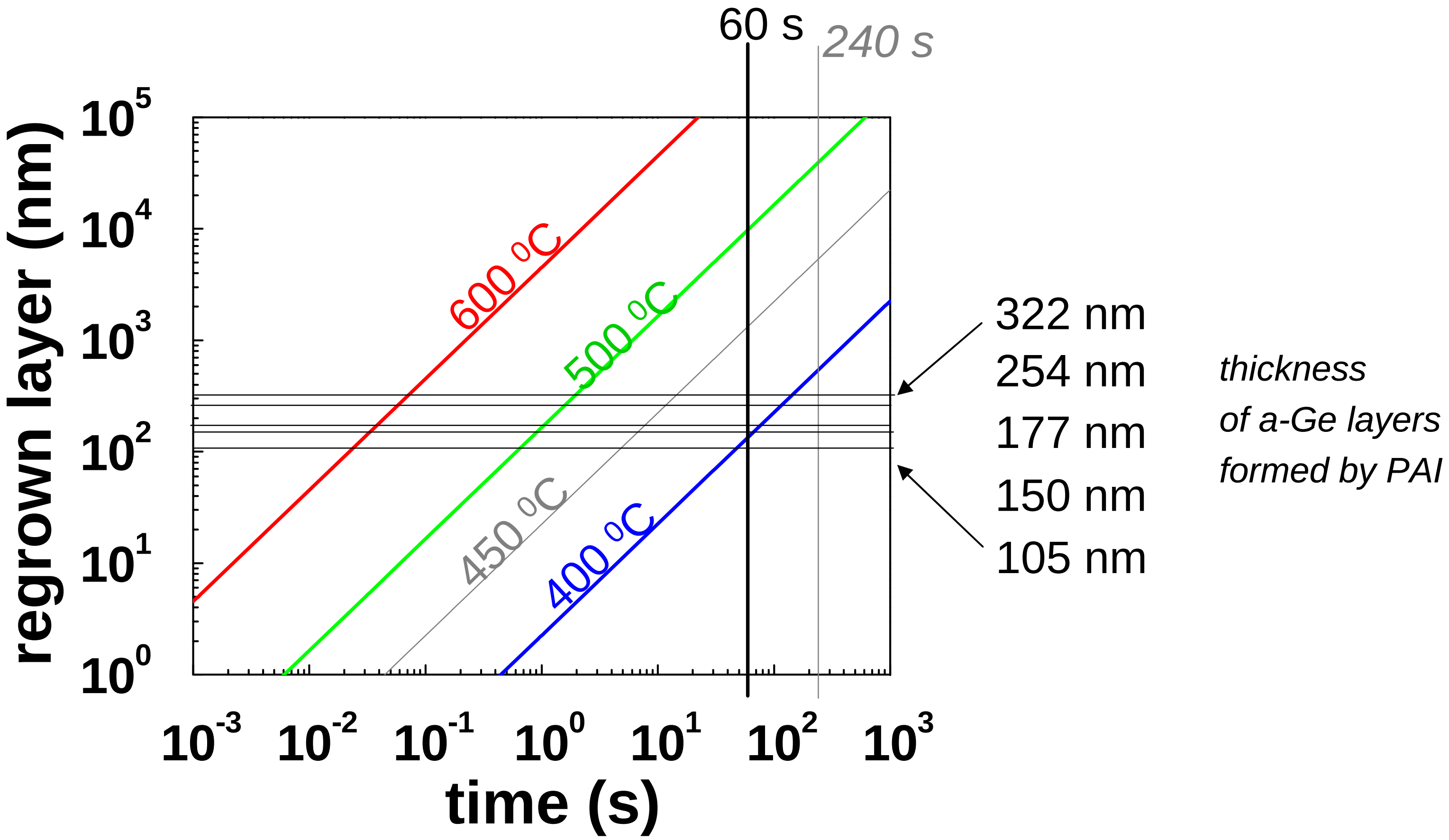
600 ^{0}C

only exception:
RTA, 400 ^{0}C
partial regrowth of the thickest layer

→ RTA and FLA lead to complete recrystallization

regrowth rate in undoped Ge (Csepregi et al. 1977):

$$\boxed{V = 5.895 \times 10^{14} \exp(-\frac{1.926\, eV}{kT})\ nm\ s^{-1}}$$



(iii) P diffusion in amorphous Ge

T > 400 ^{0}C, RTA and FLA (pre-heating):

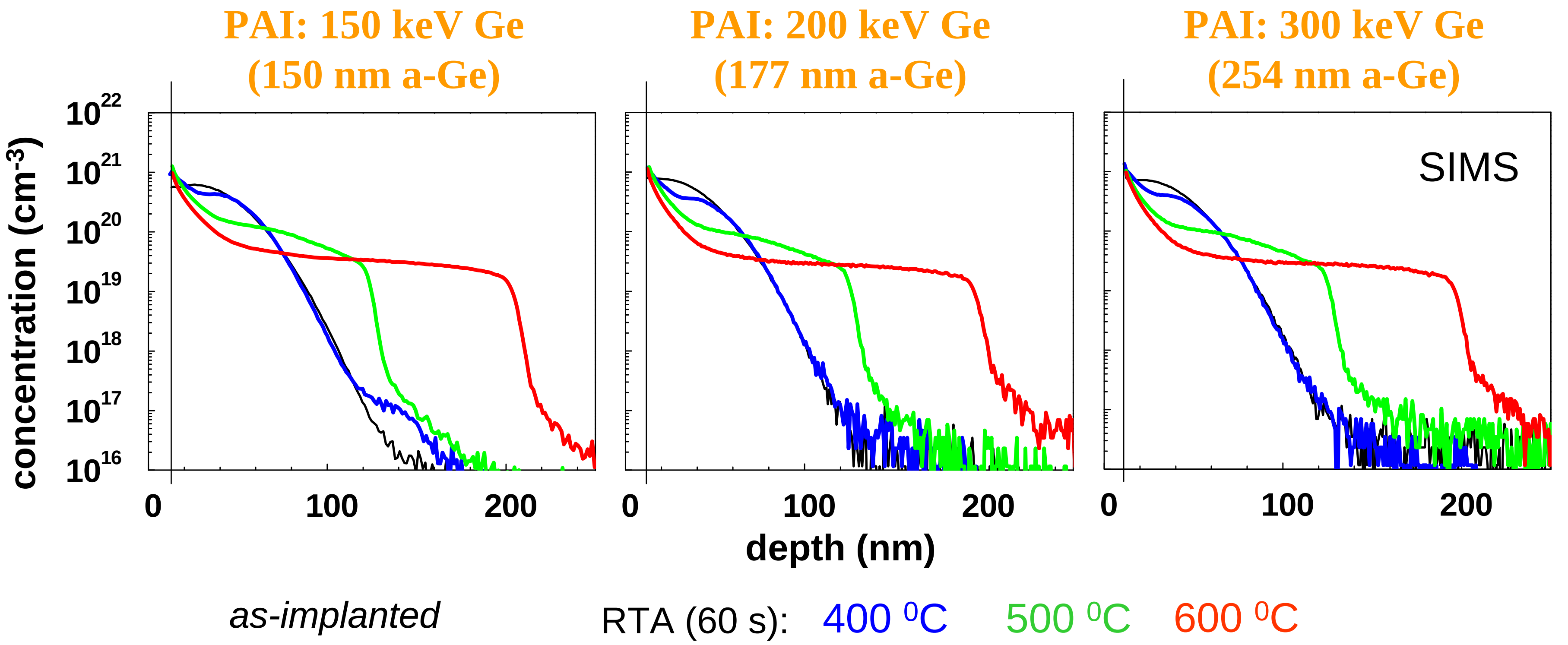
the time the implanted layer spends in c-Ge is much larger than time for SPE

T = 400 ^{0}C, RTA

the time the implanted layer spends in c-Ge is comparable with the time for SPE, but: thermal diffusion is negligible at 400 ^{0}C for <60s (see next slide)

→ diffusion in a-Ge cannot be observed

(v) concentration-dependent P diffusion in single-crystalline Ge – **RTA (I)**



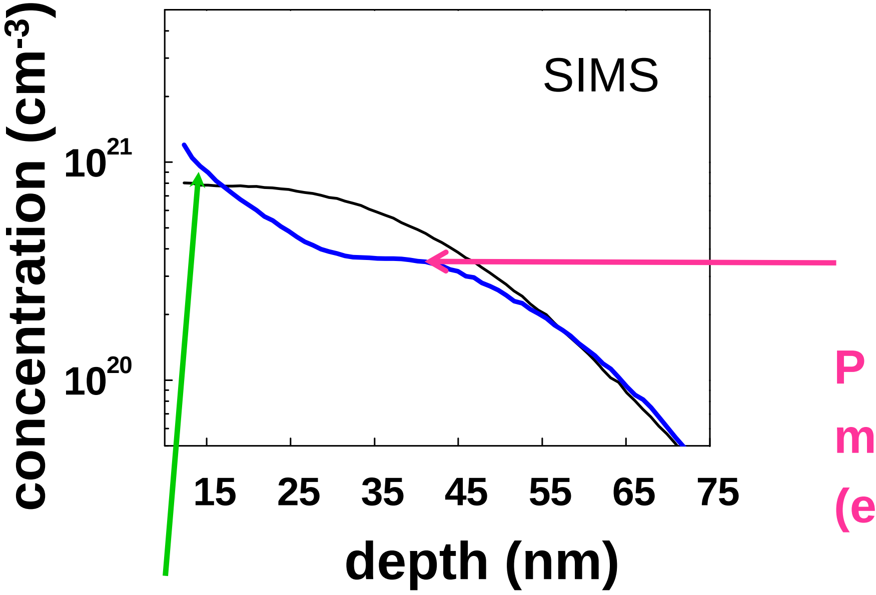
→ **measured profile broadening due to diffusion in c-Ge is independent of the thickness of the amorphous layer**

→ **diffusion of P in a-Ge is negligible**

→loss: 20% 50%

(iv) P redistribution during SPE

PAI: 200 keV Ge
(177 nm a-Ge)



comparison:

60 s RTA at 400^0C

as-implanted

$4x10^{20}$ cm^{-3}

P substitutional (?)

metastable solubility (?)

(equilibrium: $2x10^{20}$ cm^{-3})

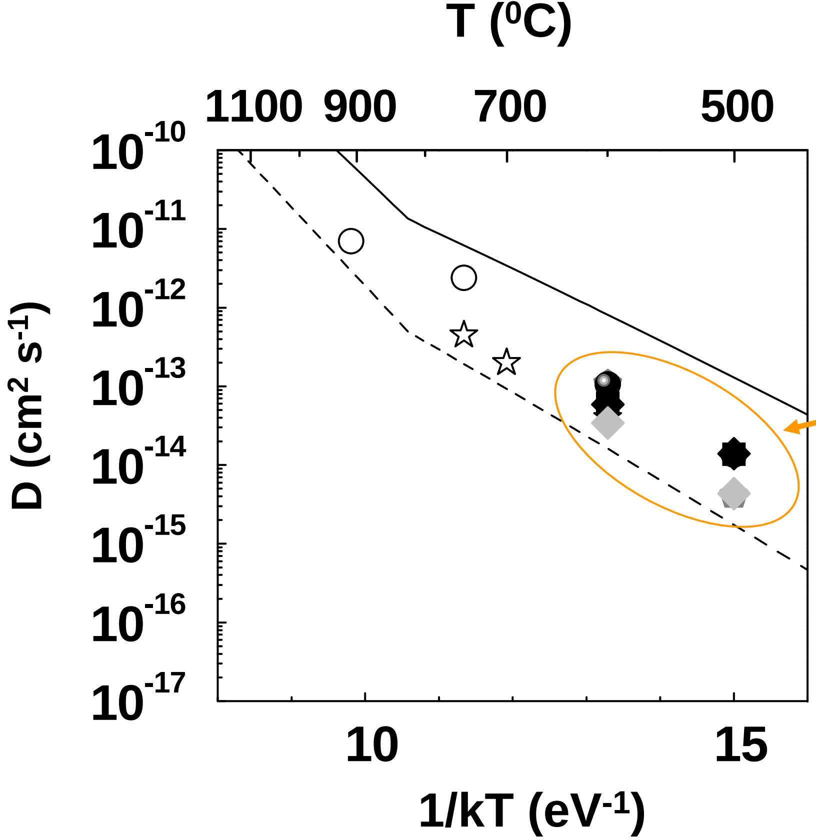
→ P is pushed ahead from moving a/c interface, *loss at interface*

consistent with
results of Satta et al. 2006

(v) concentration-dependent P diffusion in single-crystalline Ge – **RTA (II)**

diffusion coefficient at 10^{19} cm^{-3}

result of Boltzmann-Matano analysis



filled symbols: this work

RTA

open symbols: in-diffusion experiments

Matsumoto et al., 1978 ☆

Södervall et al., 1997 ○

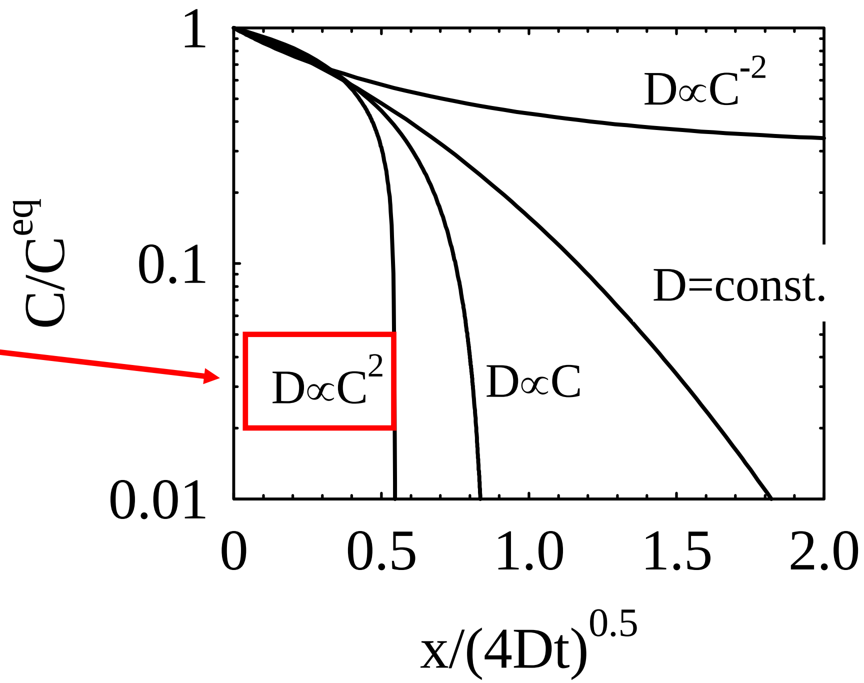
→ no significant influence of implantation defects on P diffusion

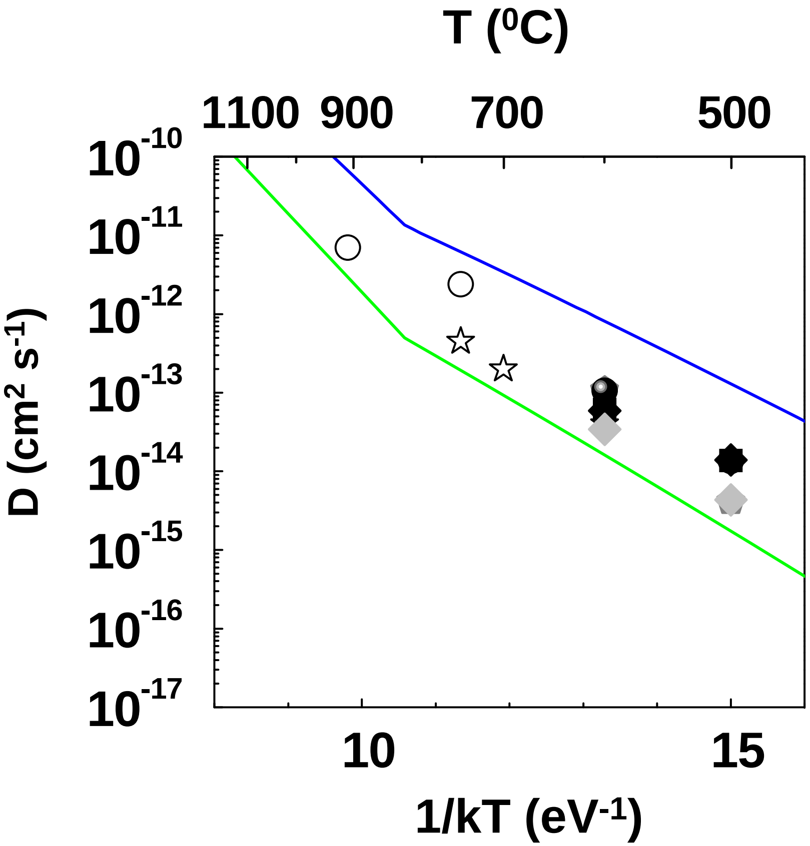
phenomenology of concentration-dependent diffusion

consideration of diffusion equation and profile shape

$$\frac{\partial C}{\partial t} - \frac{\partial}{\partial x} D \frac{\partial C}{\partial x} = 0$$

box-like shape





lines:

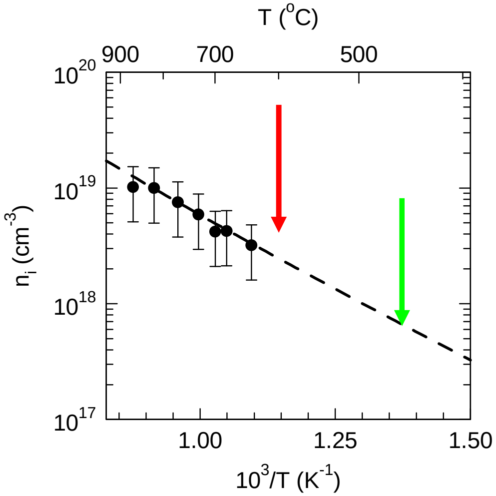
$$D = D_0 \times \left(\frac{n}{n_i} \right)^2 \qquad \text{for} \qquad n \geq n_i$$

$$D = D_0 \qquad \text{else}$$

D_0 from Chui et al. 2003 (RTA)

D_0 from Carroll et al. 2007 (FA)

$n_i(T)$ from Morin et al. 1954



onset of concentration-dependent diffusion:

RTA at 500 and 600 ^{0}C: $n_i \sim 5\times10^{17}$, 2×10^{18} cm^{-3}

diffusion mechanism (after H. Bracht 2005-2007, for As in Ge)

consideration of coupled diffusion and reaction equations for defects and P

P diffusion via the vacancy mechanism

$$\boxed{(PV)^{-} - (2+k)e^{-} \leftrightarrow P_s^{+} + V^{k}}$$

immobile: P_s^+ mobile: V^k, PV^-

in the foreign-atom controlled mode:

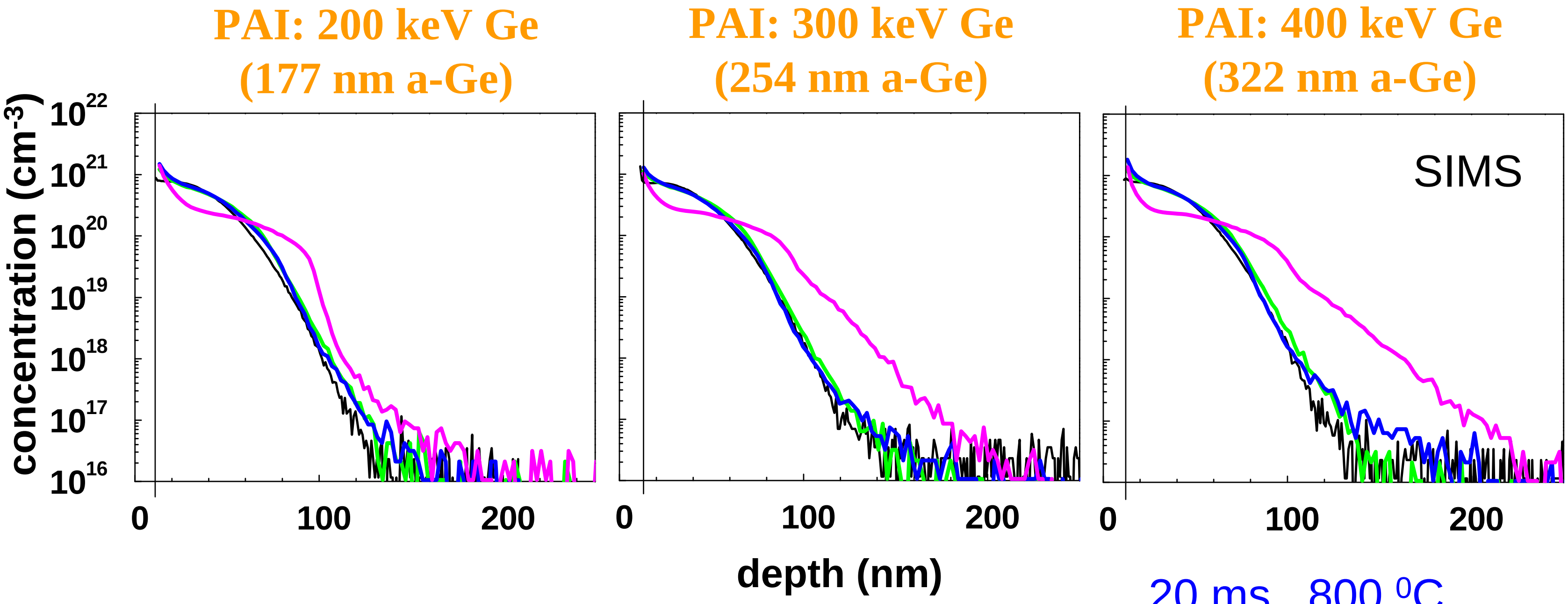
transport capacity of V^k much higher than transport capacity of PV^-

equilibrium concentration of PV^- is small compared to that of P_s^+,
local equilibrium of the above reaction, etc.

$$D = D_0 \times \left(\frac{n}{n_i}\right)^2 \quad \text{for} \quad n \geq n_i$$

$$D = D_0 \quad \text{else}$$

(v) concentration-dependent P diffusion in single-crystalline Ge -- **FLA**


PAI: 200 keV Ge (177 nm a-Ge)

PAI: 300 keV Ge (254 nm a-Ge)

PAI: 400 keV Ge (322 nm a-Ge)

as-implanted

FLA: 240 s pre-heating at 400 ^{0}C

20 ms, 800 ^{0}C

3 ms, 900 ^{0}C

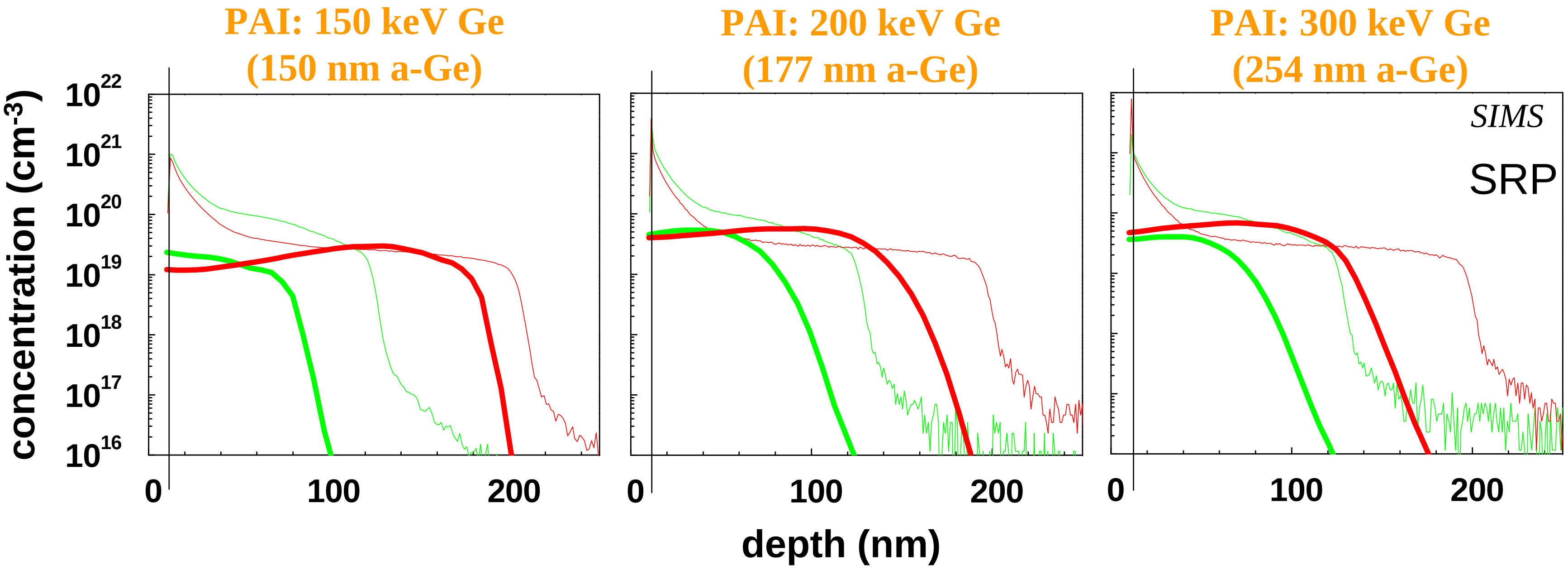
20 ms, 900 ^{0}C

→ additional tail diffusion depends on the thickness of the amorphous layer

→ influence of defects remaining after SPE (transient state) ???

→loss:
30%

(vi) activation of P -- **RTA**



RTA (60 s): 500 ^{0}C 600 ^{0}C

→ depth dependent activation from <1% to 100%

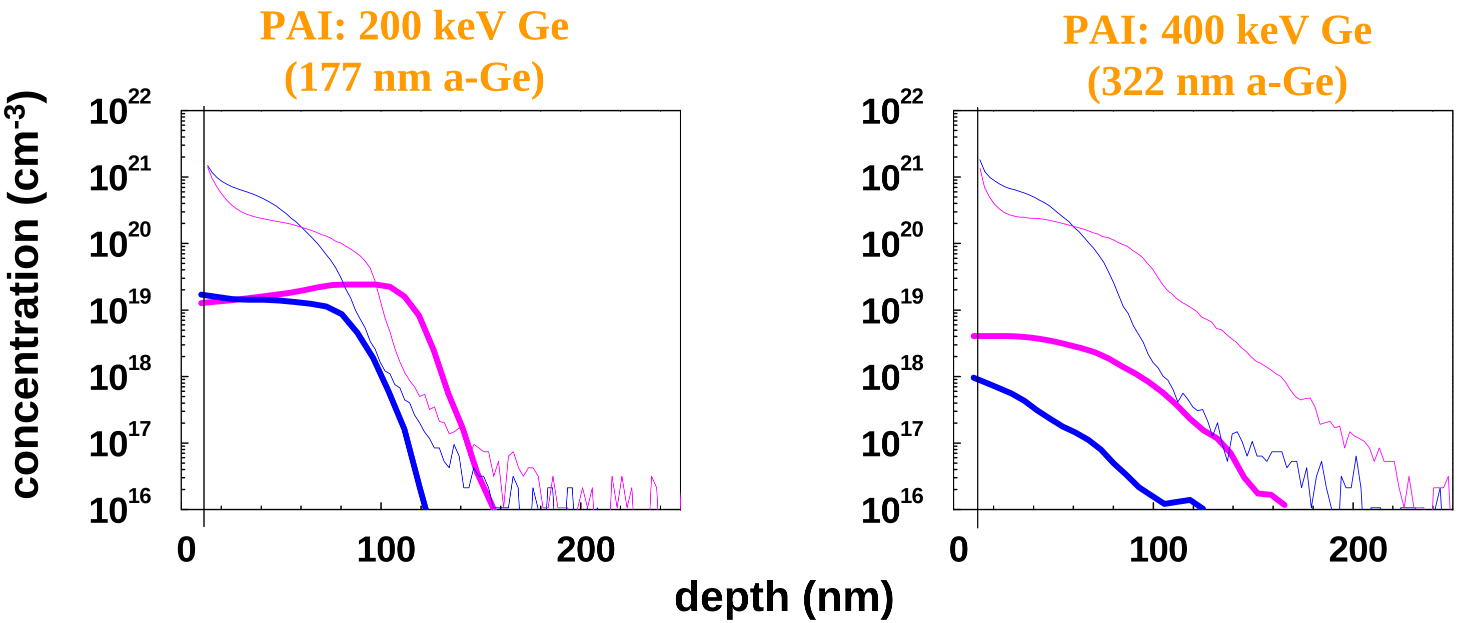
reasons for strong deactivation:

Simoen et al. 2006

(i) P-V acceptor centers

(ii) formation of P-V and/or GeP clusters above the solubility limit (2×10^{20} cm^{-3})

(vi) activation of P -- **FLA**



PAI: 200 keV Ge
(177 nm a-Ge)

PAI: 400 keV Ge
(322 nm a-Ge)

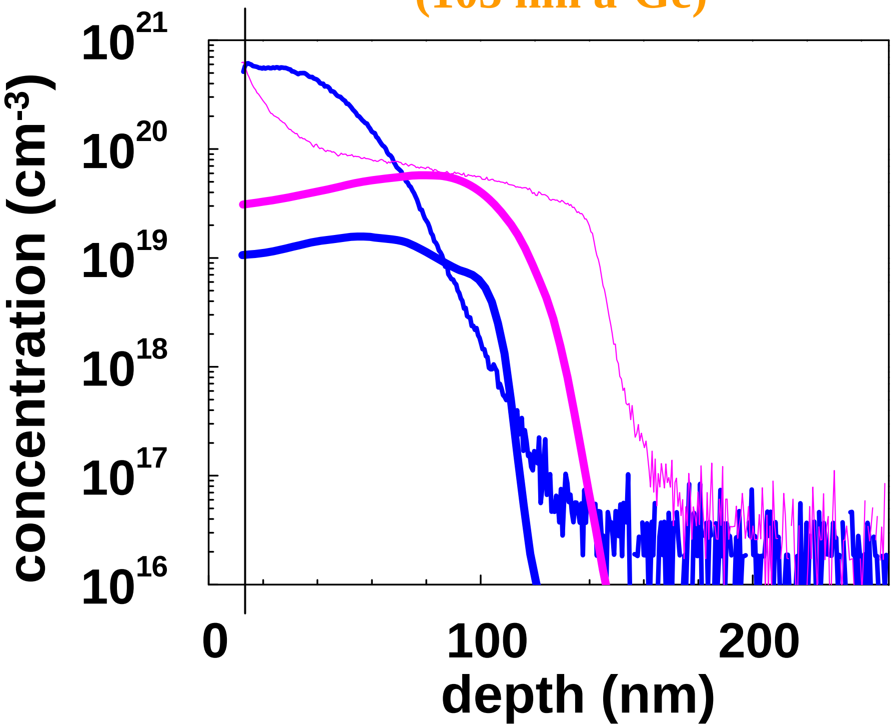
FLA: 240 s pre-heating at 400 ^{0}C

20 ms, 800 ^{0}C

20 ms, 900 ^{0}C

→**degree of activation depends on the thickness of the pre-existing amorphous layer**

PAI: 100 keV Ge
(105 nm a-Ge)



FLA:

240 s pre-heating at 400 ^{0}C 20 ms, 800 ^{0}C

240 s pre-heating at 450 ^{0}C 20 ms, 900 ^{0}C

→best result for mixed RTA+FLA

depth of the n^+p junction (**Xj**, determined at a donor concentration of 10^{17} cm^{-3}),
maximum electrical activation (**ma**), average electrical activation (**aa**), and sheet resistance (**R_s**)

Ge PAI	**60 s RTA, 600 ^{0}C**					**pre-heating: 240 s, 400 ^{0}C (*450 ^{0}C),** **FLA: 20 ms , 900 ^{0}C**				
Energy (keV)	**X_j (nm)**	ma (10^{19} cm^{-3})	aa (%)	**R_s(Ω)**	**R_s(Ω) (Hall)**	**X_j (nm)**	ma (10^{19} cm^{-3})	aa (%)	**R_s(Ω)**	**R_s(Ω) (Hall)**
100	**186**	2.8	27	**100**	**54**	**139***	5.8*	35*	**60***	**51***
150	**196**	3.0	28	**88**	**45**	**-**	-	-	**-**	**-**
200	**180**	7.2	40	**55**	**-**	**144**	2.5	10	**100**	**-**
300	**163**	6.9	34	**55**	**-**	**-**	-	-	**-**	**-**
400	**156**	5.6	32	**75**	**-**	**134**	0.41	1.5	**600**	**-**

Summary

P implantation into pre-amorphized Ge and subsequent annealing:

- SPE regrowth occurs already at the lowest thermal budget
- fast P redistribution during SPE regrowth
- P diffusion in a-Ge cannot be observed
- concentration-dependent P diffusion in c-Ge is the main cause for profile broadening and P loss towards the interface
- mechanism of concentration-dependent P diffusion: vacancy mechanism in the foreign-atom controlled mode

- additional diffusion component in the tail region obtained after FLA could be related to defects remaining after SPE

- FLA: degree of activation depends on the thickness of the pre-existing amorphous layer

- RTA: maximum activation 3 – 7x10^{19} cm^{-3},

  R_s: 50 -100 Ω, X_j: 160 – 200 nm

- best result: mixed RTA+FLA: 6x10^{19} cm^{-3},

  R_s: 60 Ω, X_j: 140 nm