Modeling of pulsed Laser Thermal Annealing for junction formation optimization and process control

YOU INVENT, WE ACHIEVE

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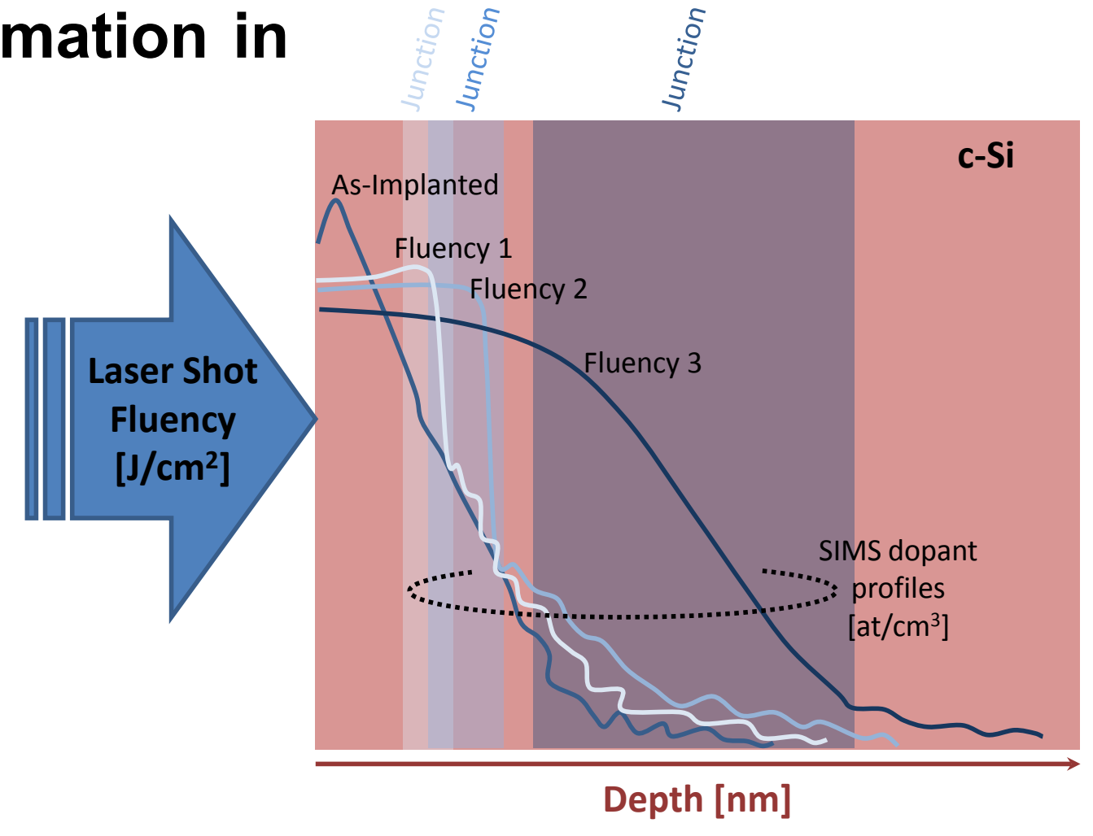
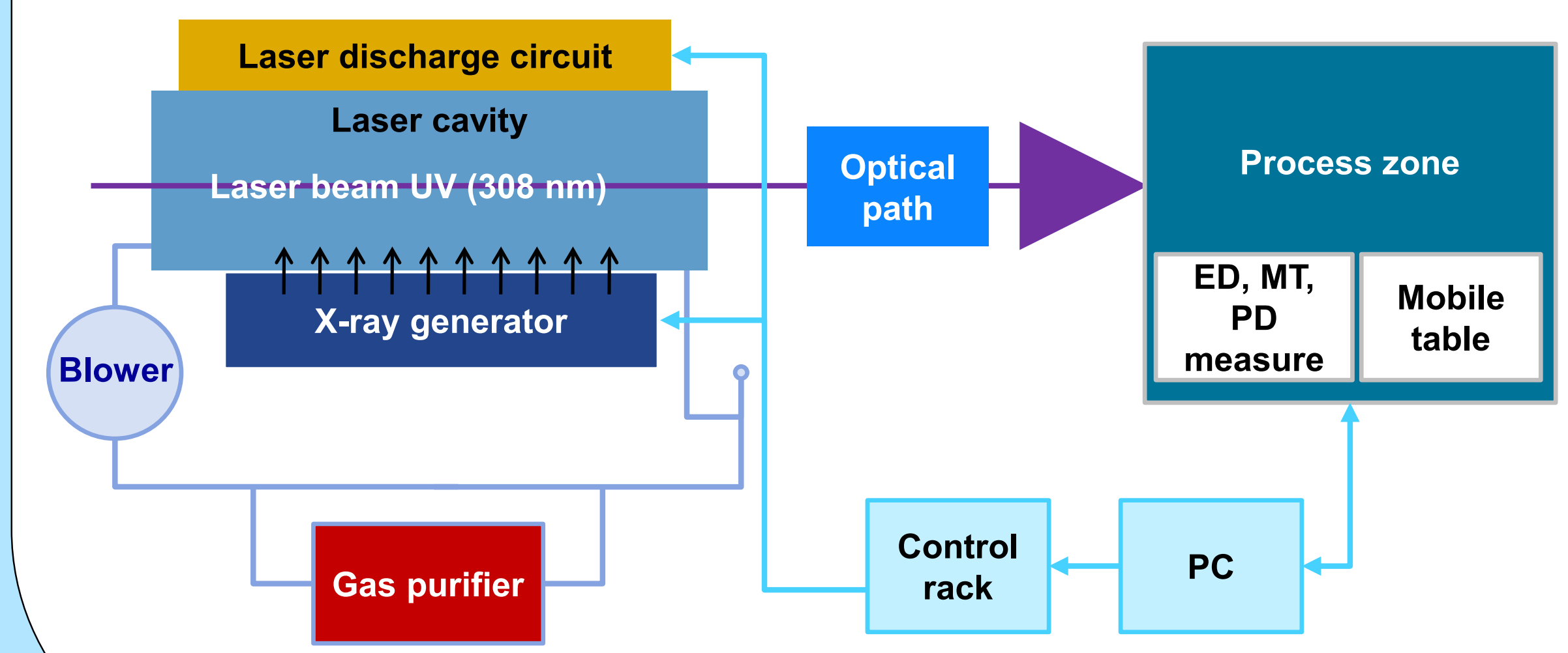
Introduction

Laser Thermal Annealing (LTA) is a technique for junction formation in process fabrication of semiconductor devices:

- Low thermal budget
- Melt and recrystallization of c-Si
- Box-like dopants profiles with high activation (>90%)
- Ultrafast (~µs)





EXCICO LTA technology:

- Gas laser
- Pulsed laser at 308nm wavelength
- Pulse duration (PD) is of ~150ns
- High energy density (ED), up to 3J/cm² for up to 20x20mm²
- Melt depth (MD) depends on ED and PD

Gas laser technology challenge is the time stability.

Parameters to adapt and control the laser process:

- Electrical discharge
- Gas mix (others are constructive, not subject of this study)

Levers impact can be translated in ED shift and PD change.

Customer targets (not measured in-situ):

- Junction depth, similar to MD
- Interface temperature

LTA process simulation:

- Correlates laser control with targets
- Provide process window

Problem solved under COMSOL Multiphysics for bulk c-Si:

- 1D finite element particular system of PDE
- Problem divided in two:
  - ➢ Thermal behavior and phase-change
  - ➢ Boron diffusion and segregation
    - SIMS are used to estimate MD

Model validity and accuracy when PD and ED change is analyzed (similar to the levers impact)

Thermal problem: Phase-Field model

Phase-Field formalism

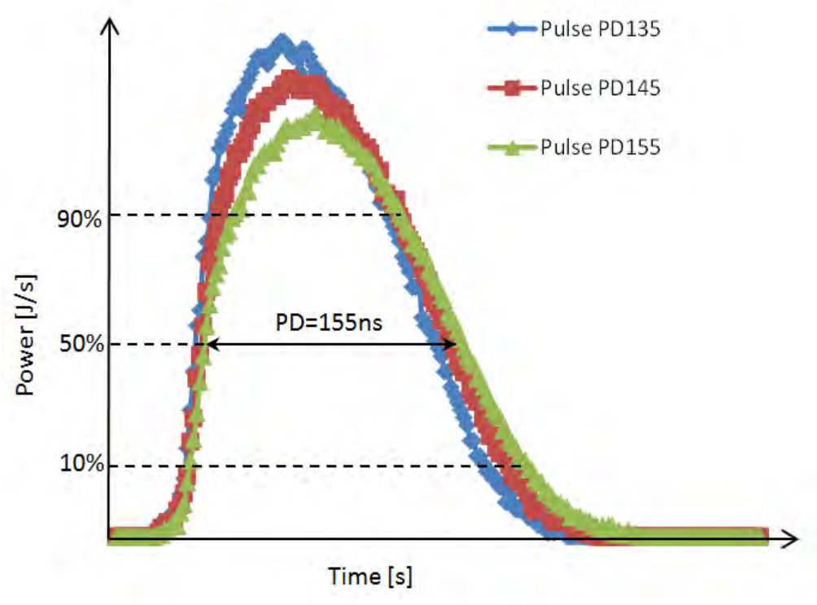
$$\underbrace{-1 \leq}_{\text{Pure liquid}} \varphi \underbrace{\leq +1}_{\text{Pure solid}}$$

- Heat equation:

$$\rho C_p \frac{\partial T}{\partial t} - \nabla^2(KT) = \frac{\rho L_{fus}}{2}\frac{15}{8}(\varphi^2-1)\frac{\partial \varphi}{\partial t} + S(x,t)$$

$$S(x,t) = E_{las}P(t)(1-R)\alpha e^{-\alpha x}$$

(External heat source)



- Phase-Field equation:

$$\tau \frac{\partial \varphi}{\partial t} = W^2\nabla^2\varphi - \varphi(\varphi^2-1) - \lambda \frac{C_p}{L_{fus}}(T-T_M)(\varphi^2-1)^2$$

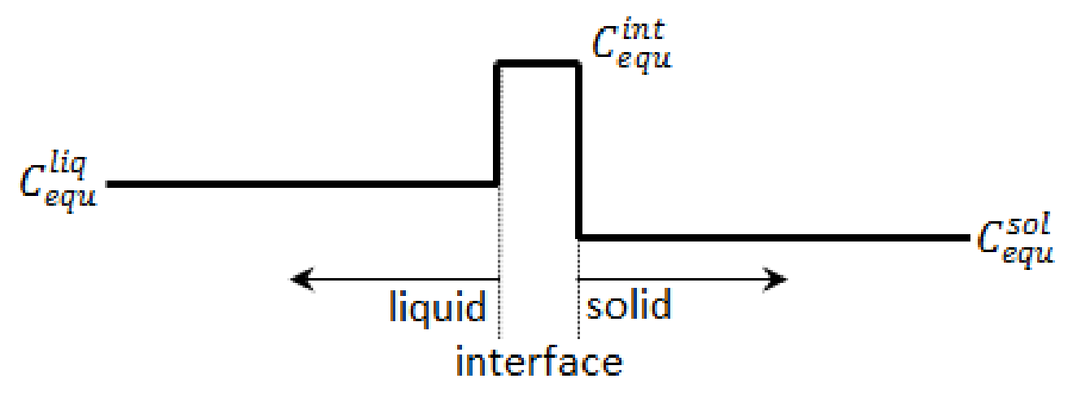
[Karma and Rappel, PRE 1998] [La Magna et al., JAP 2004]

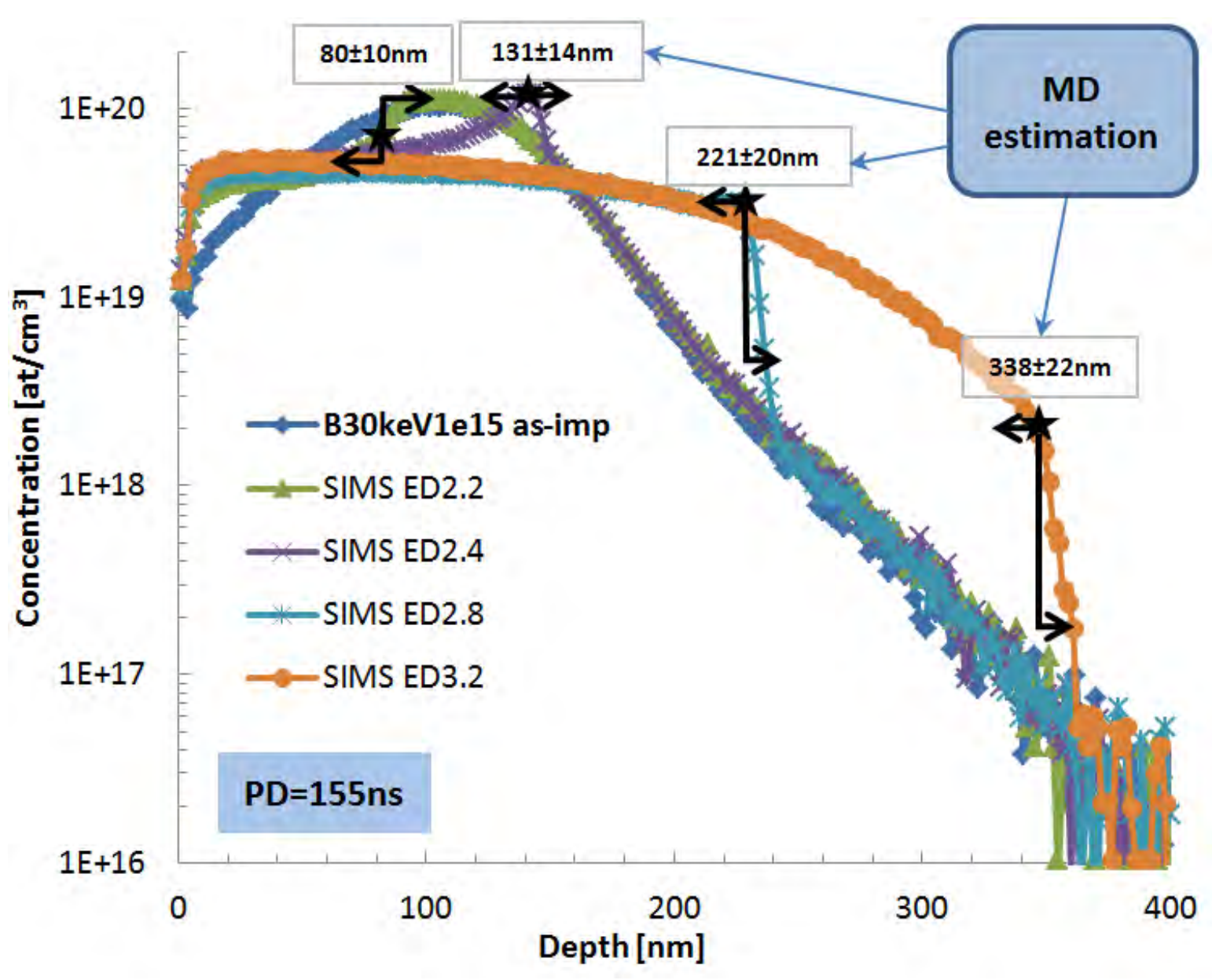
Diffusion and segregation problem: Adsorption model

- Diffusion + adsorption equation:

$$\frac{\partial C_B}{\partial t} = \nabla(D_B \nabla C_B) - \nabla\left(D_B \frac{C_B}{C_{equ}}\nabla C_{equ}\right)$$

Boron adsorption at liquid/solid interface



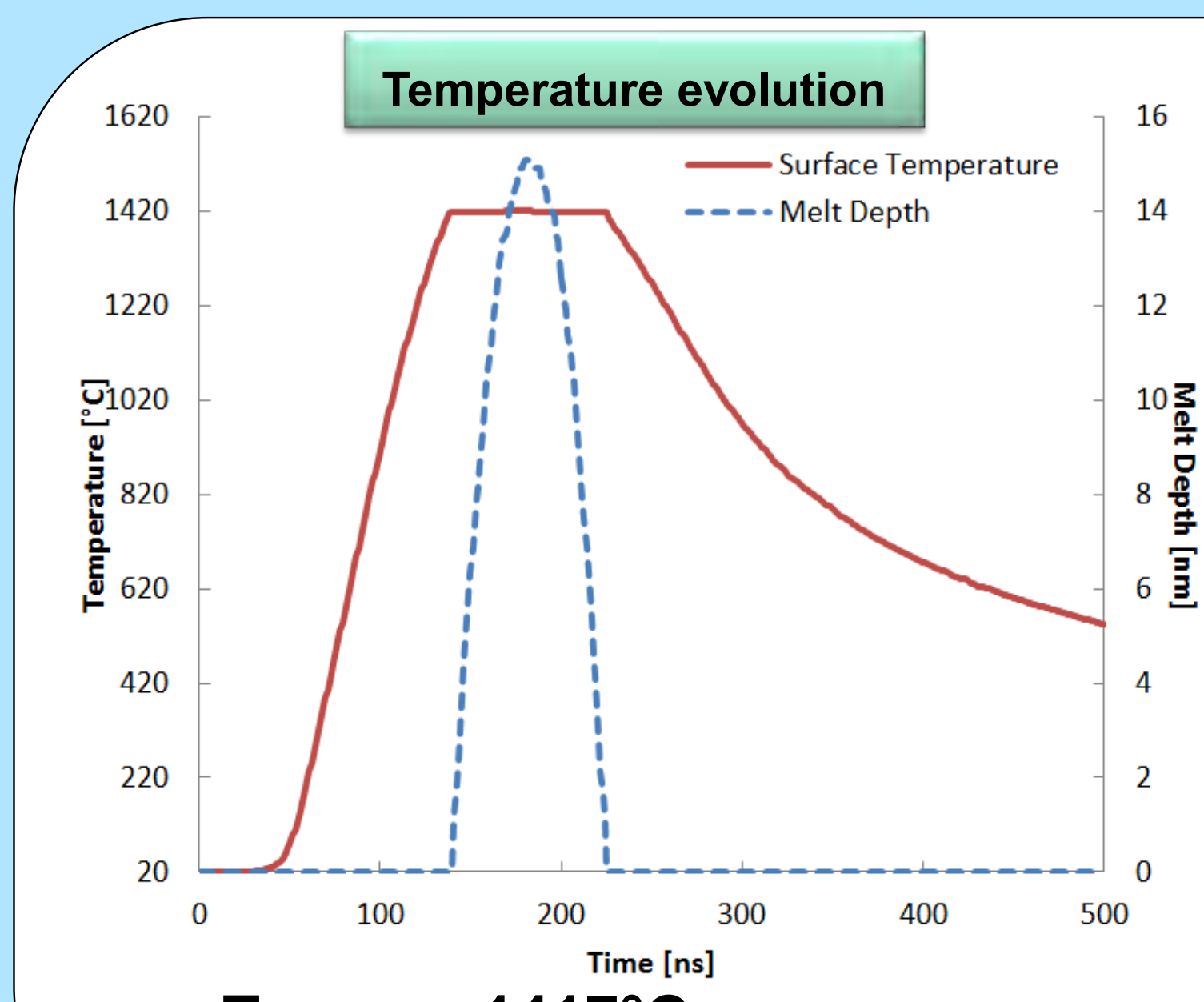


MD±ΔMD estimation from SIMS (profiles obtained by means of one pulse laser irradiation)

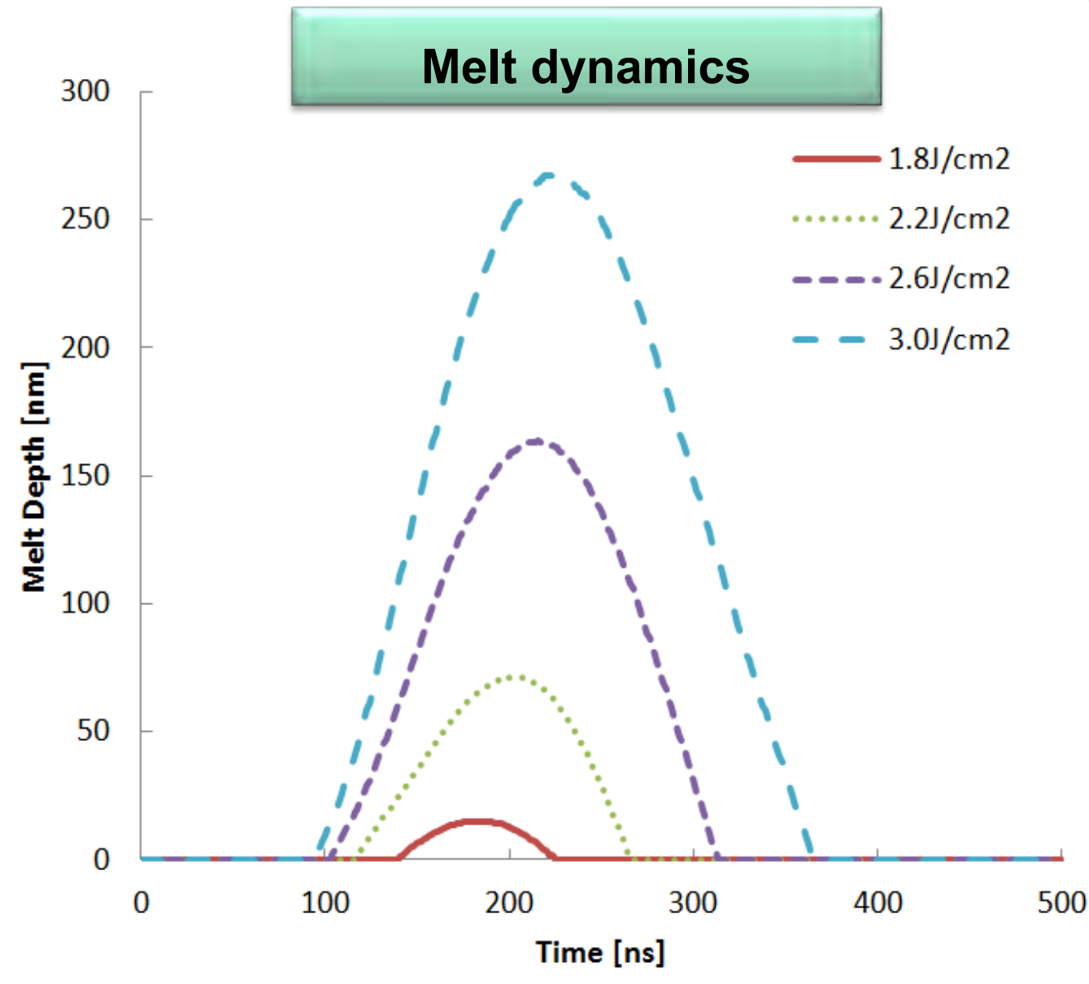
[H. M. You, et al., JAP 1993] [M. Hackenberg, R. Negru, K. Huet, et al., IIT 2012]

Thermal simulation

Temperature evolution

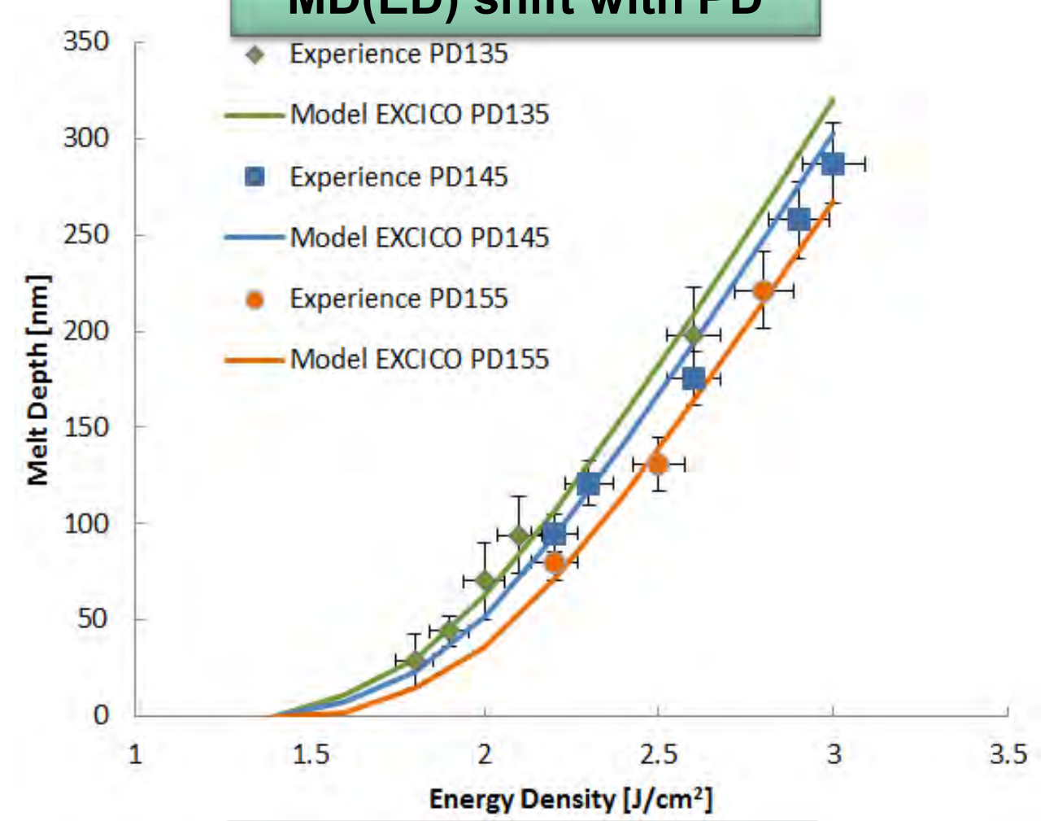


Melt dynamics

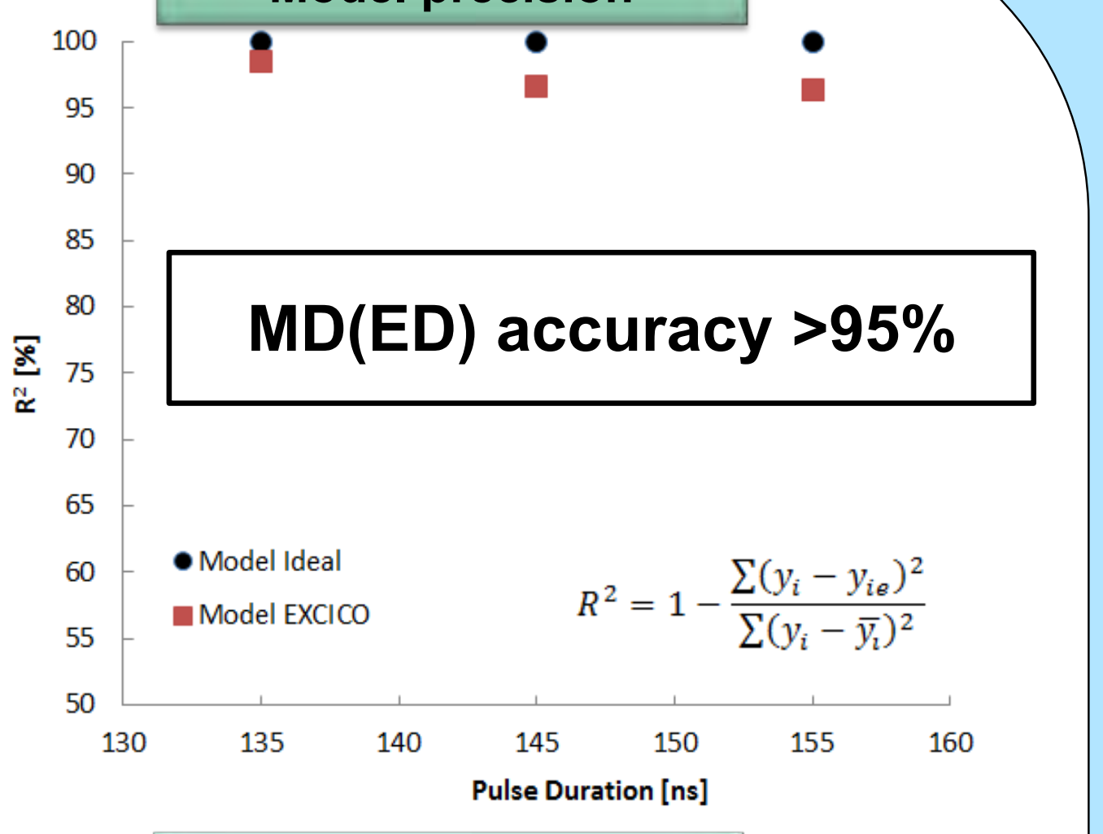


- $T_{melt\ c\text{-}Si}$: 1417°C
- Tents of ns to reach melting temperature

MD(ED) shift with PD



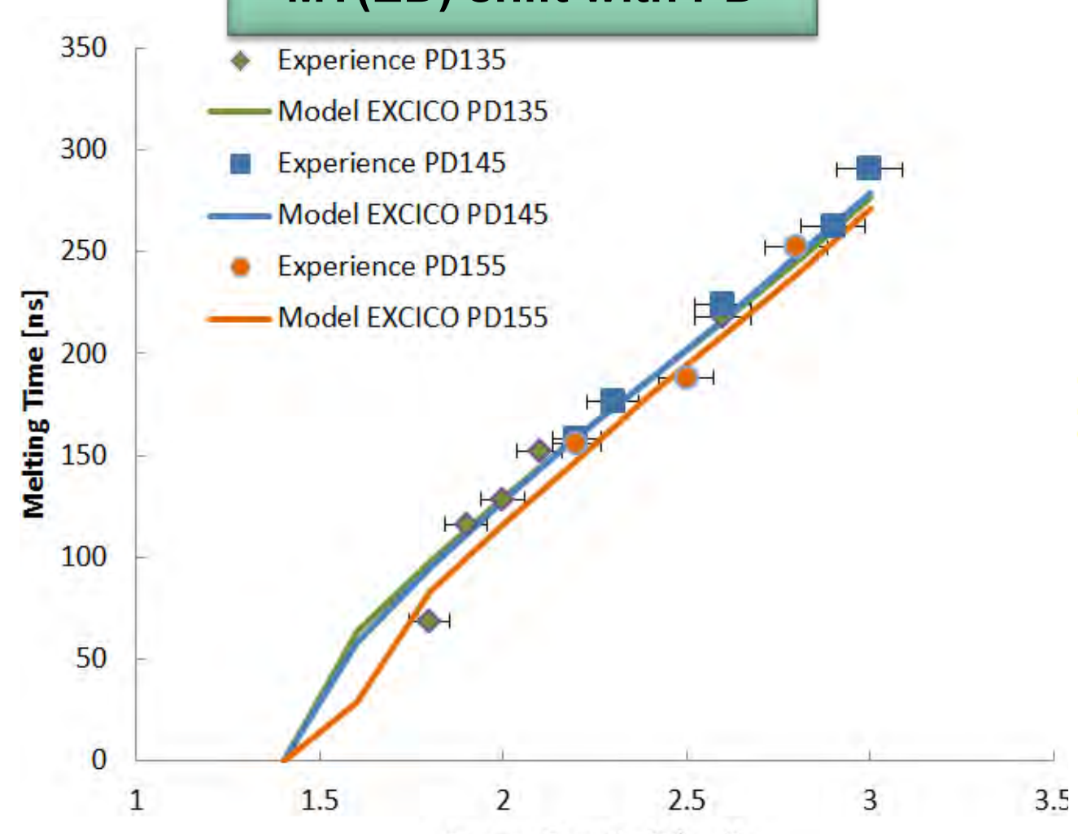
Model precision



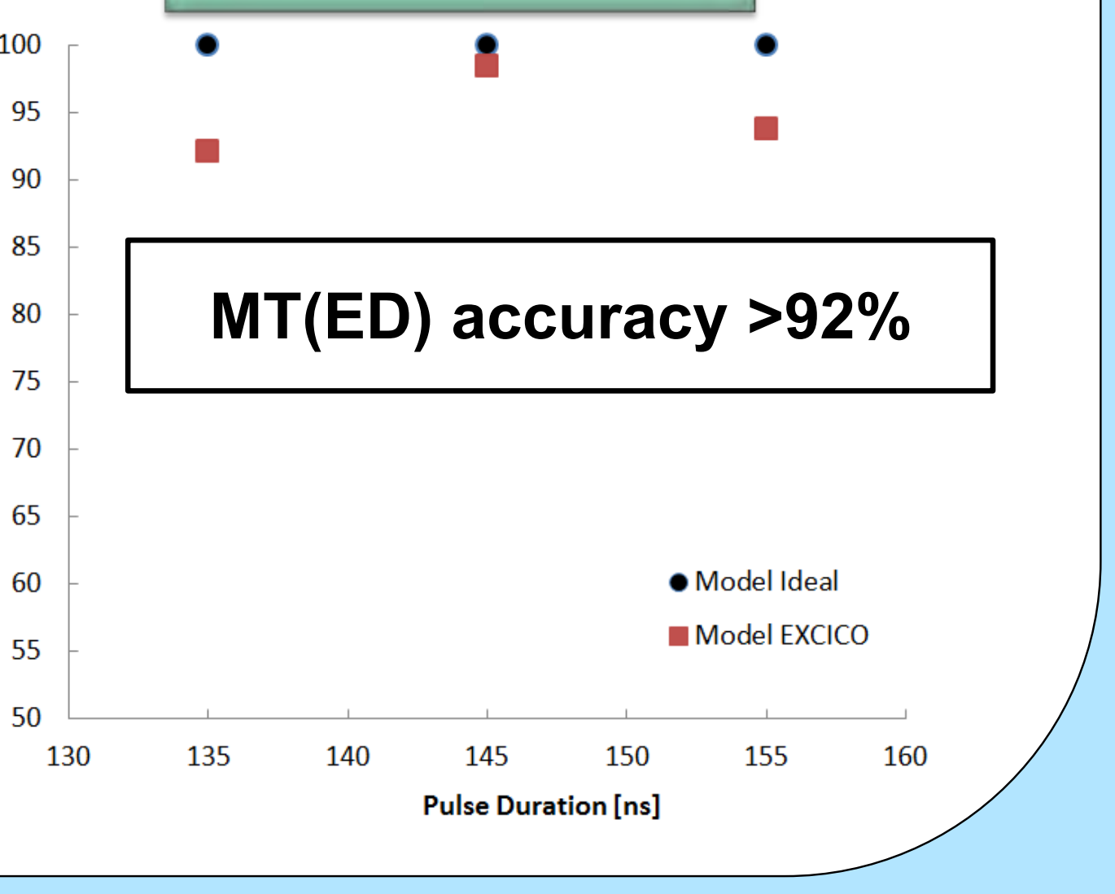
MD(ED) accuracy >95%

$$R^2 = 1 - \frac{\sum(y_i - y_{ie})^2}{\sum(y_i - \bar{y}_i)^2}$$

MT(ED) shift with PD

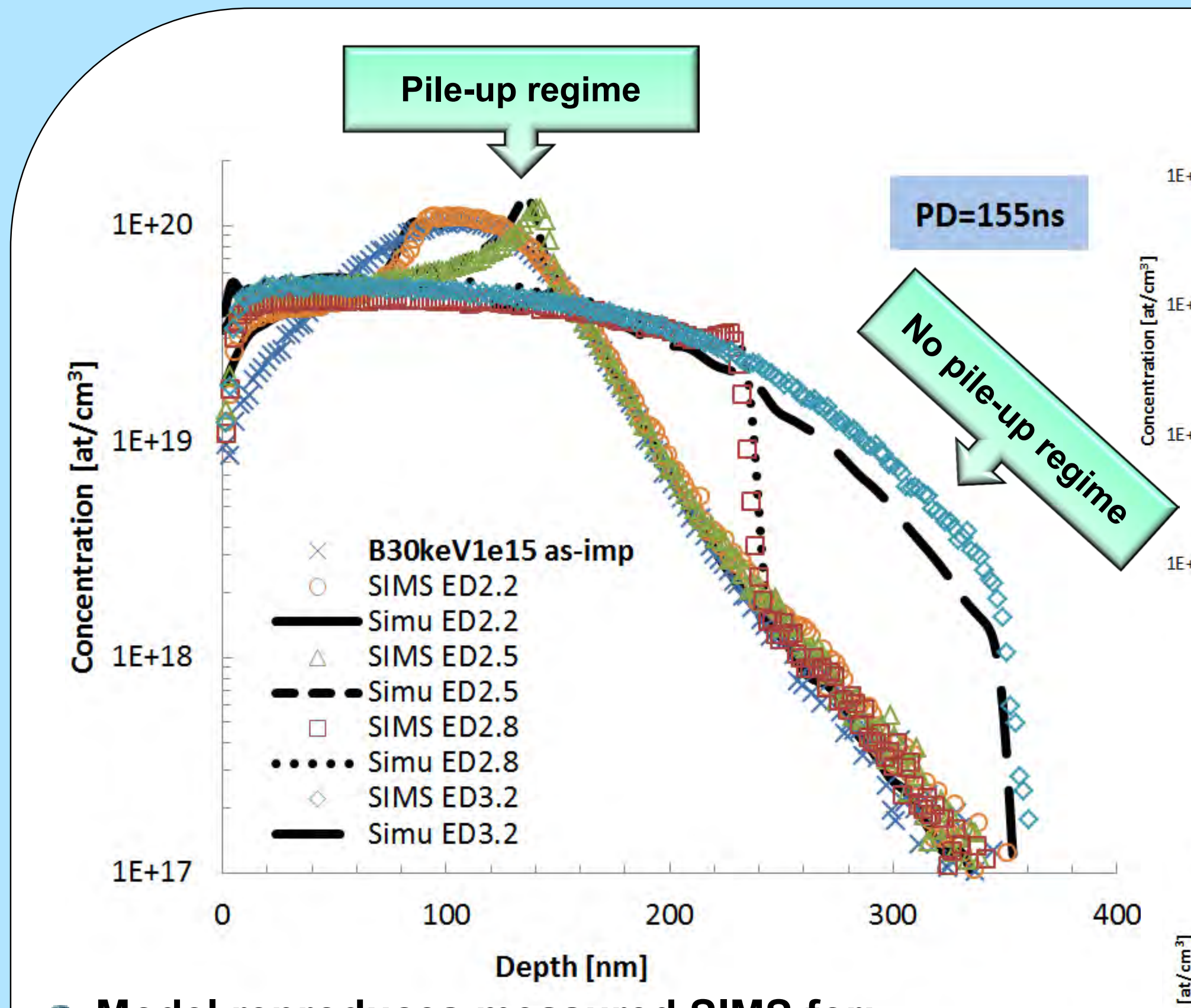


Model precision



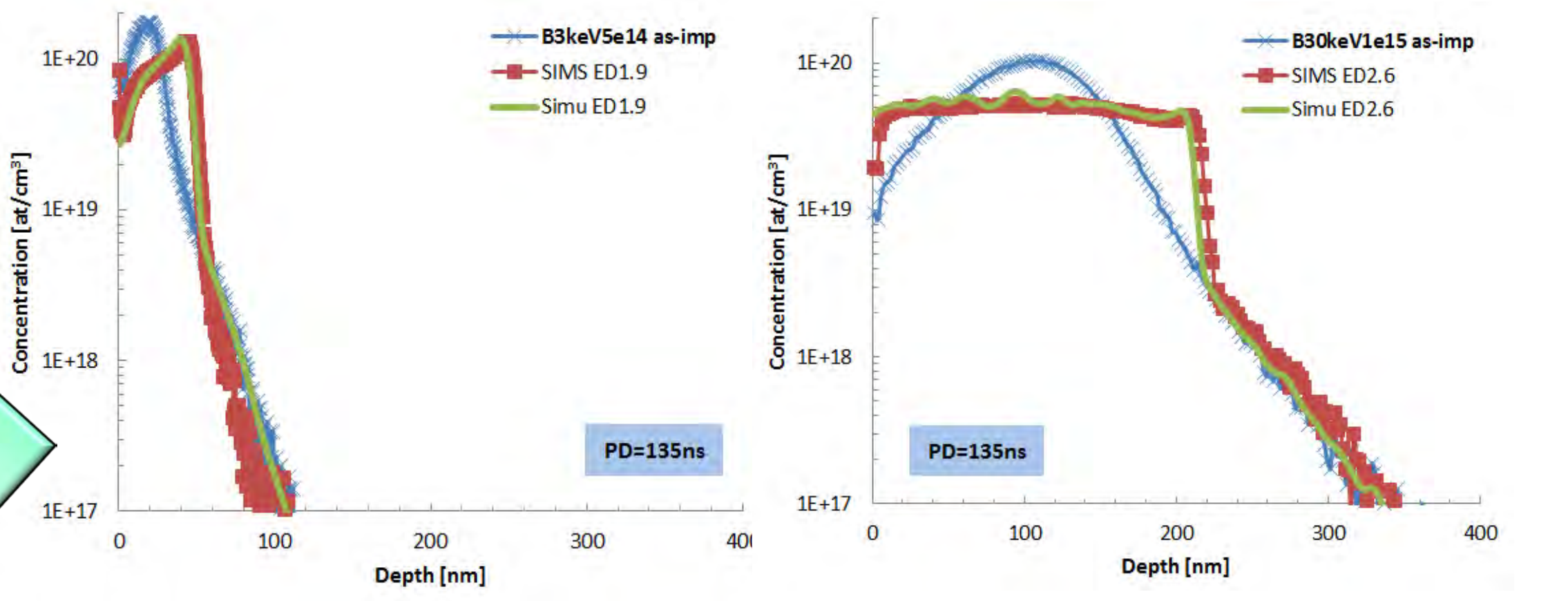
MT(ED) accuracy >92%

Boron segregation and diffusion modeling

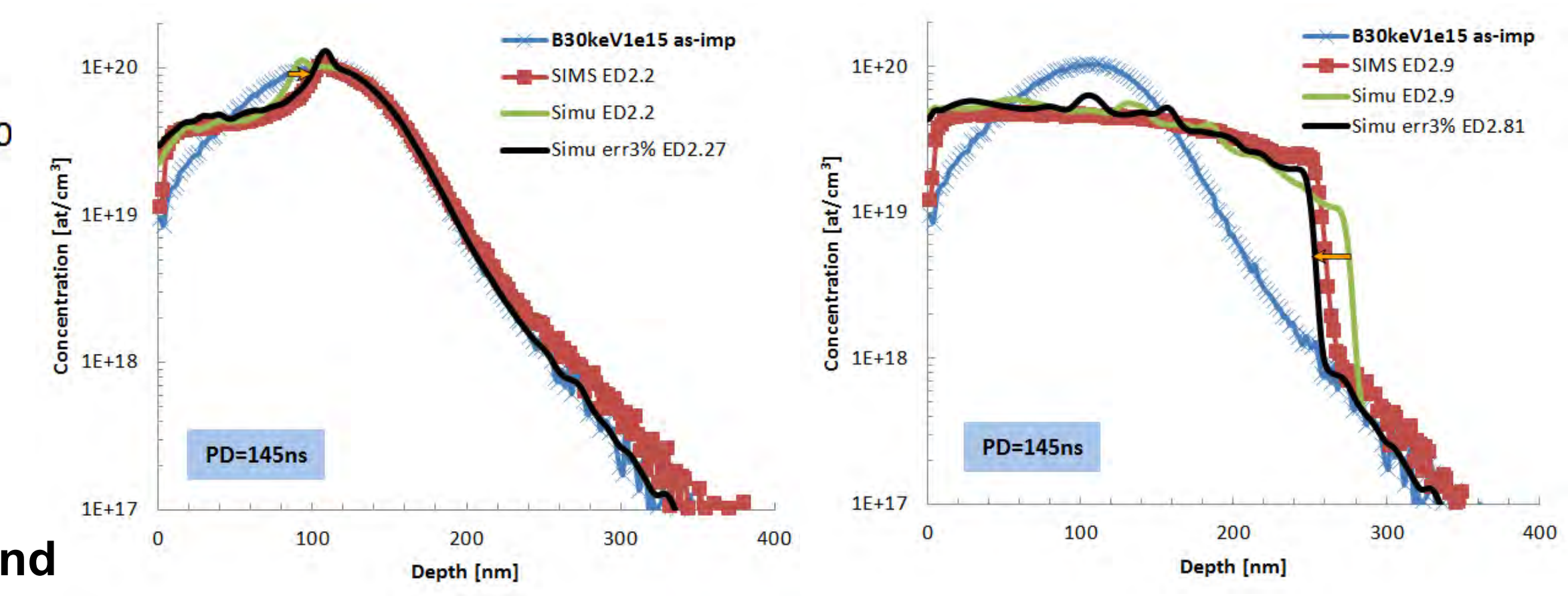


- Model reproduces measured SIMS for:
  - ➢ Different implant conditions
  - ➢ LTA ED range
- Good simulation of pile-up phenomenon
- Model is reliable for PD change between 135ns and 155ns

- Model validity with implant conditions:



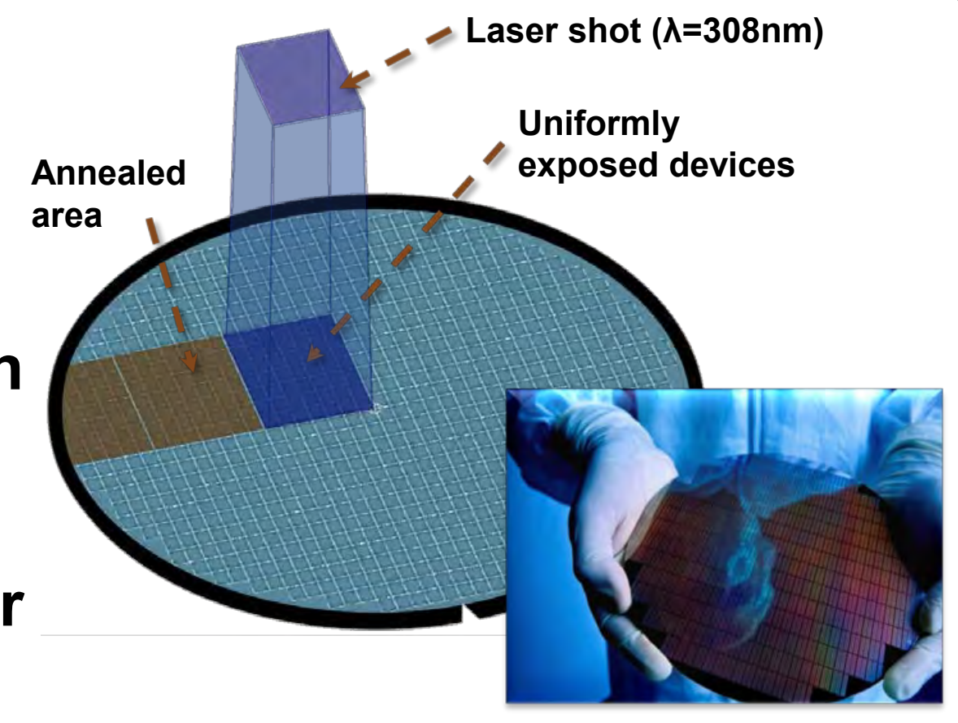
- Model reliability in ED±3% process variability:



Boron simulated profiles accuracy is >90%

Conclusions

- Presented model was developed for EXCICO LTA process for bulk c-Si:
  - ➢ Follow the process variability inherent for gas lasers
  - ➢ Thermal and adsorption models provide results with over 90% accuracy
  - ➢ Adsorption model reproduces the experimental scenario for Boron diffusion and segregation
- Was analyzed the feasibility to furnish a process monitoring software for optimization and control of non-measurable parameters such as melt depth



Excerpt from the Proceedings of the 2012 COMSOL Conference in Milan