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

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OUTLINE

- **Laser Thermal Annealing technology**
- **Experiments**
- **Model**
  - Phase-Field approach
  - Dopant diffusion and segregation
- **Results**
- **Conclusions**

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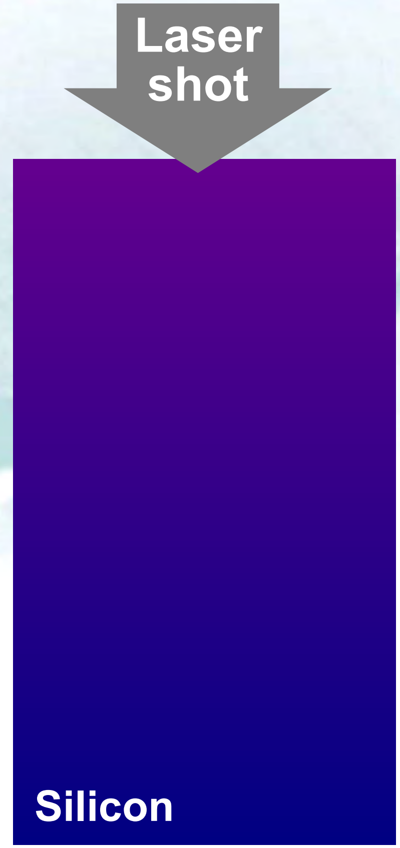
Pulsed excimer Laser Thermal Annealing (LTA)

⇨ **Technique for junction formation in process fabrication of semiconductor devices**

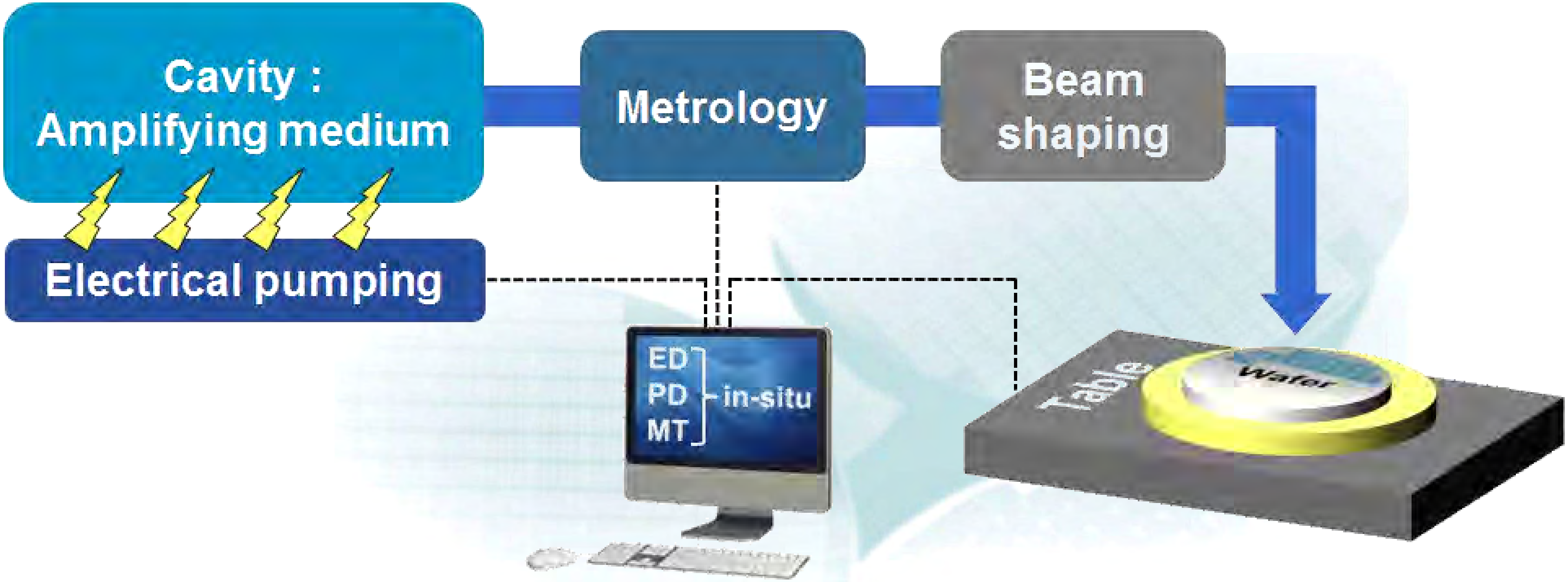


- **Laser absorption**
- **Melting and recrystallization**

Low thermal budget process

- **High temperature localized in space and time**
  - ❖ Shallow depth effect (<µm)
  - ❖ Ultrafast (<µs)

Laser tool characteristics

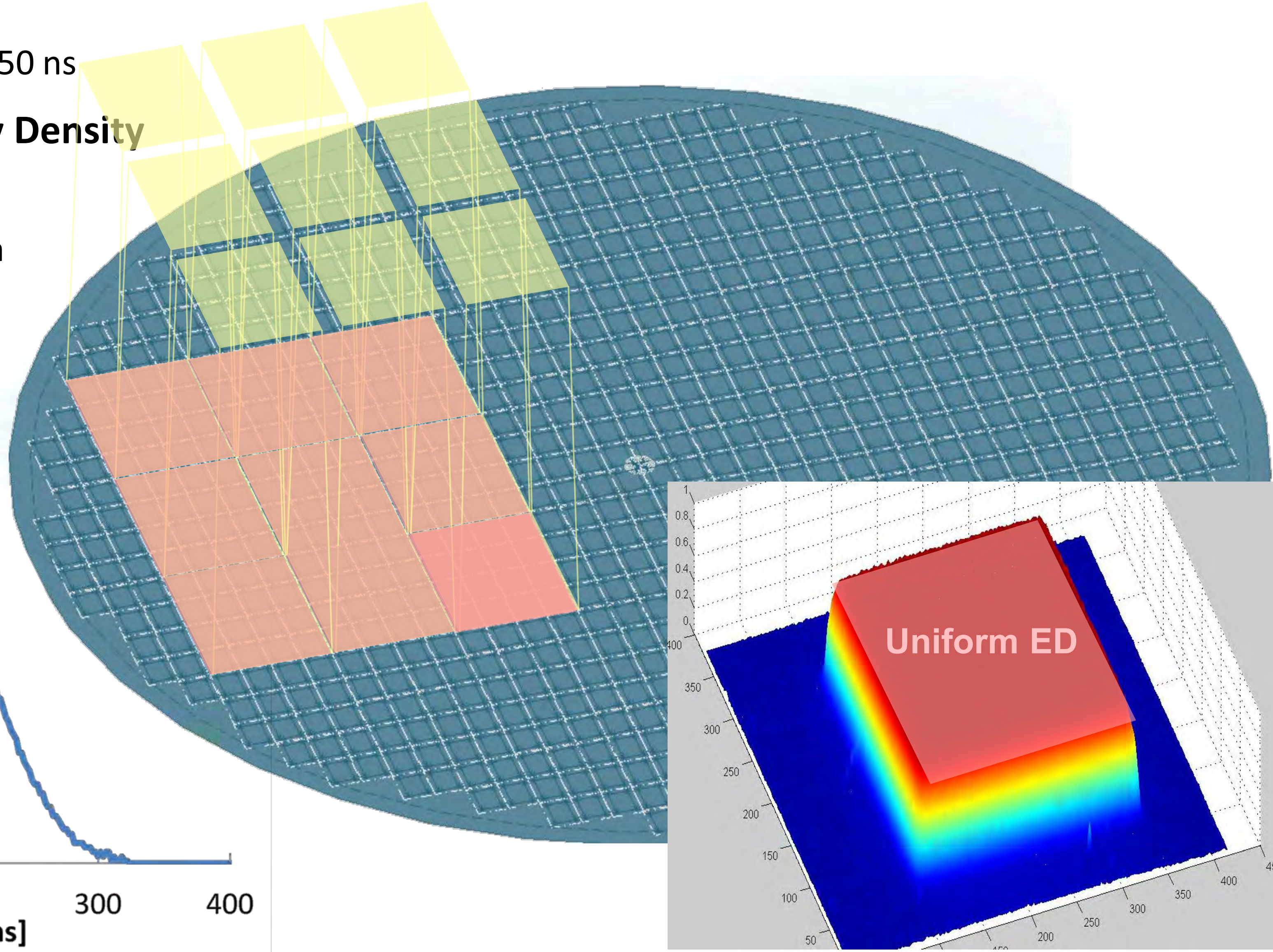


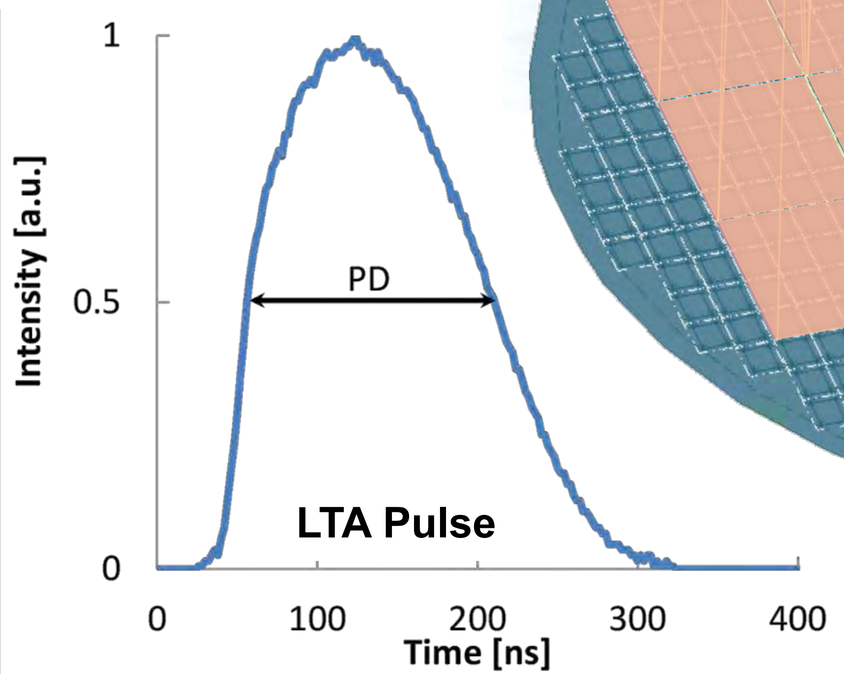
- **High Energy Gas laser**
  - XeCl excimer gas
  - UV 308nm wavelength
  - Pulsed
- **Challenge: process variability**

⇨ **Energy and pulse variations**

Laser Thermal Annealing Process Parameters

- **Long pulse laser**
  - Pulse Duration: ~150 ns
- **Uniform high Energy Density**
  - Up to 3 J/cm^2
  - Up to 2x2 cm^2 area



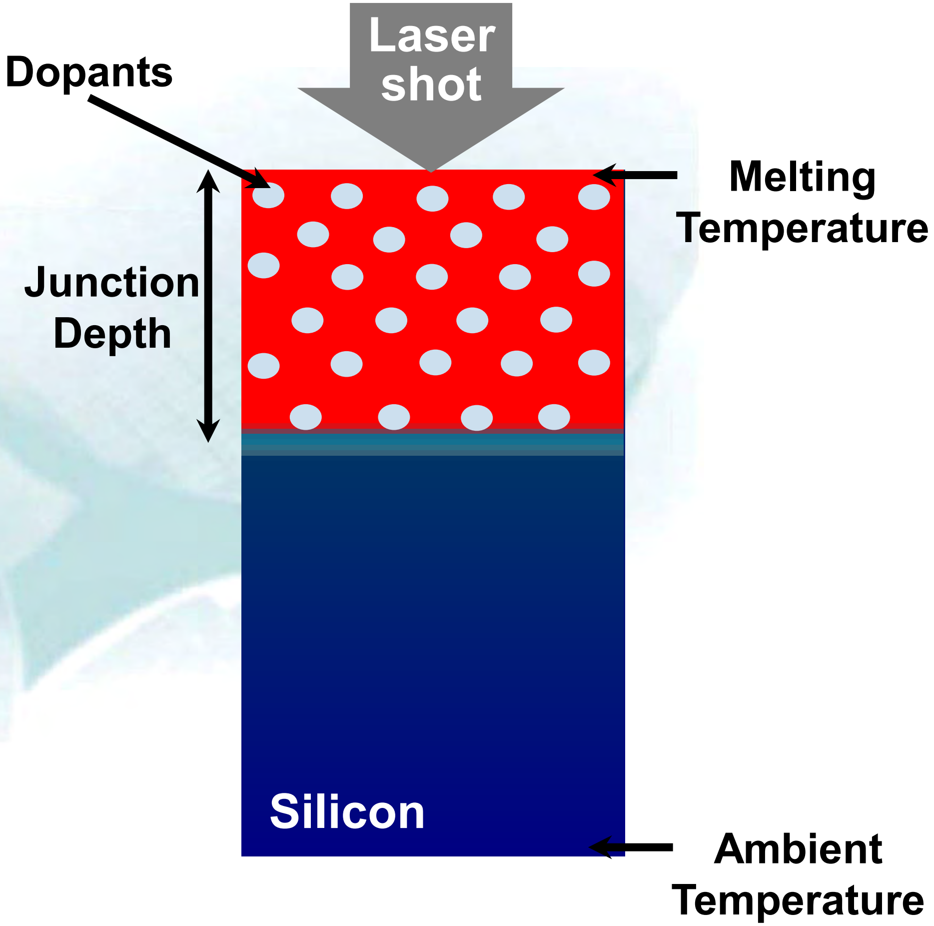


Process variability and junction formation

- **Other** laser annealing **process parameters**
  - **Melt Depth** (ex-situ measurement)
  - **Temperature** (no direct measurement)

- Depend on
  - Laser **Energy Density**
  - **Pulse** shape

⇒ **LTA process simulation**
  - **Linking tool parameters to process**
  - **Understanding process variability**



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LTA simulation: 2 steps

Thermal step

Laser parameters

+

Structure
- *Material properties*
- *Geometric dimensions*

Process Window determination to avoid damage

- **Temperature profiles**
- **Melt dynamics**

Diffusion step

Temperature profiles & Melt dynamics

+

- *Dopant profiles*

Junction formation

- **Dopant distribution**

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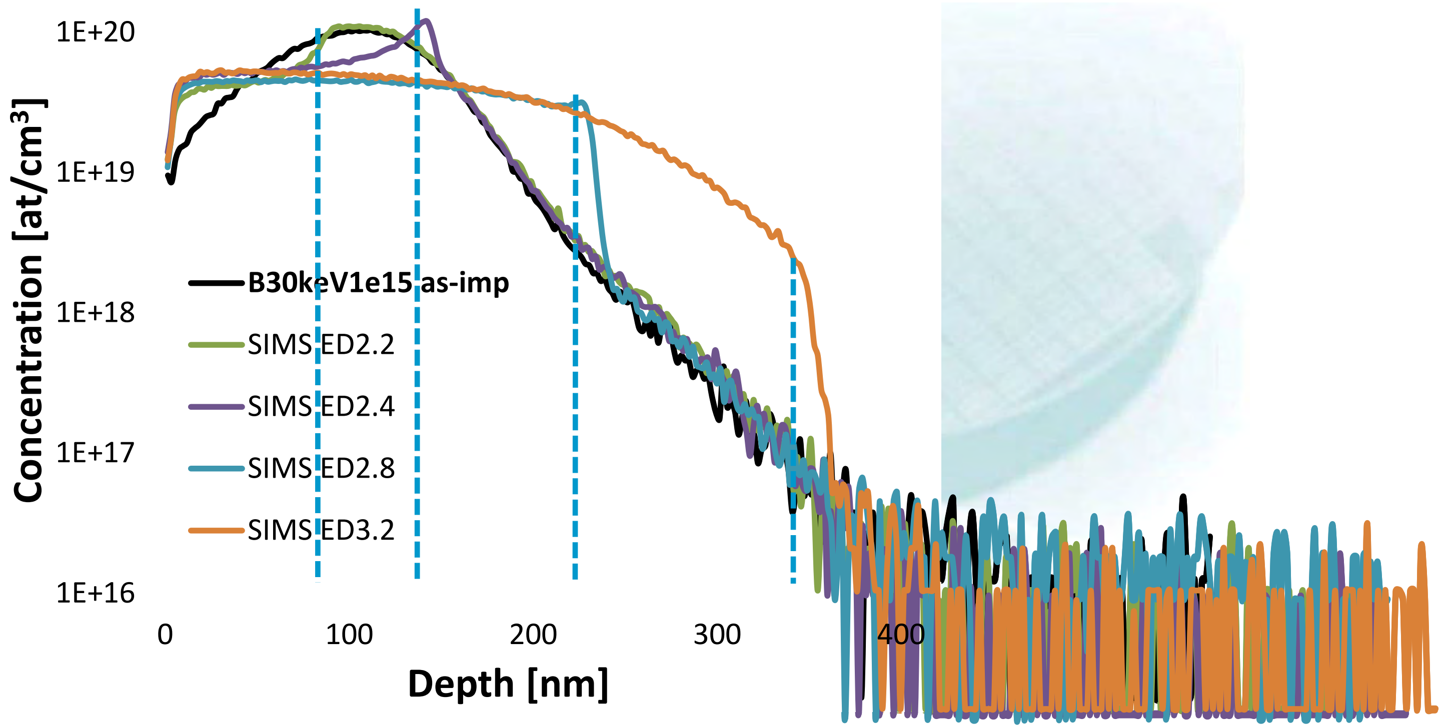
Typical Boron profiles after LTA



- Melt Depth estimation vs Energy Density
- Profiles not explained by simple diffusion (Fickian)

Secondary Ion Mass Spectroscopy (SIMS) error:
±5% in depth and ±10 in concentration

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Thermal and phase change simulation

Phase-Field model

- **Heat (T) and Phase (φ) equations are connected by coupling terms**
- Formalism: $-1 \leq \varphi \leq +1$ (−1: **Pure liquid**; +1: **Pure solid**)
- **Heat equation**

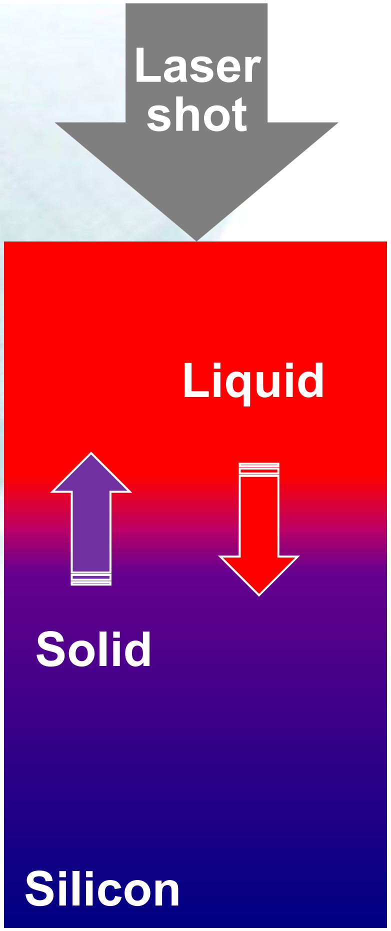
$$\rho \cdot c_p \cdot \frac{\partial T}{\partial t} - \nabla^2 (k \cdot T) = \overbrace{\rho \cdot \frac{L_{fus}}{2} \cdot \frac{15}{8} \cdot \left(\varphi^2 - 1\right)^2 \cdot \frac{\partial \varphi}{\partial t}}^{\text{Coupling with phase}} + S(x,t)$$

Source equation

$$S(x,t) = ED \cdot P_n(t) \cdot (1 - R) \cdot \alpha \cdot e^{-\alpha \cdot x}$$

- **Phase change equation**

$$\tau \cdot \frac{\partial \varphi}{\partial t} = W^2 \cdot \nabla^2 \varphi - \varphi \cdot (\varphi^2 - 1) - \overbrace{\lambda \cdot \frac{c_p}{L_{fus}} \cdot (T - T_M) \cdot (\varphi^2 - 1)^2}^{\text{Coupling with temperature}}$$



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

Dopant distribution simulation

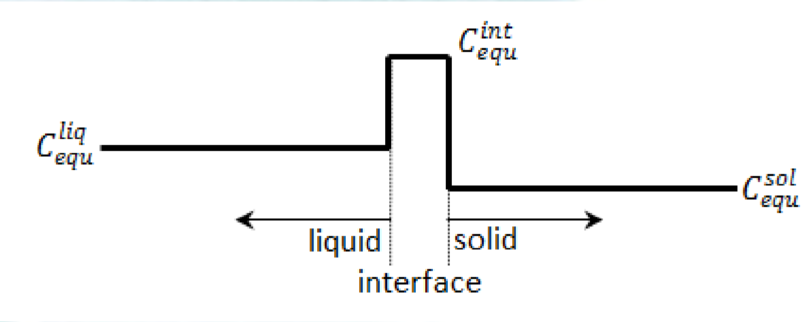
⇨ Diffusion + Adsorption model

- ❖ Boron adsorbed at Liquid/Solid interface

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

Fickian diffusion

Adsorption and segregation



- With
  - ❖ C_B: Boron concentration (cm^{-3})
  - ❖ D_B: Boron diffusion coefficient (cm^2s^{-1}, phase dependent)
  - ❖ C_{equ}: Equilibrium concentration (**fit parameter**)

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

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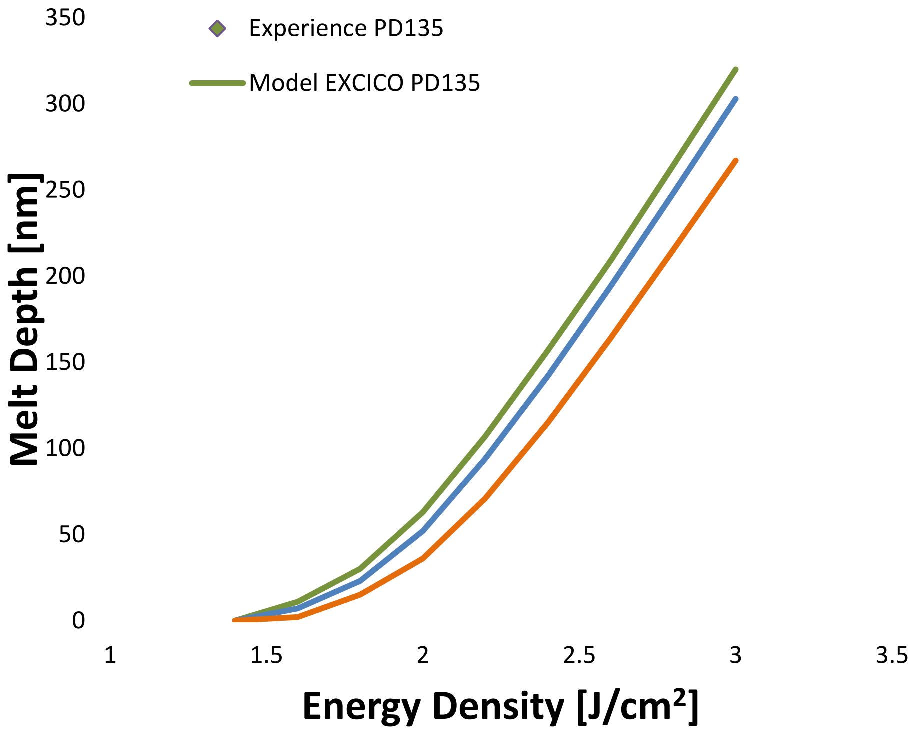
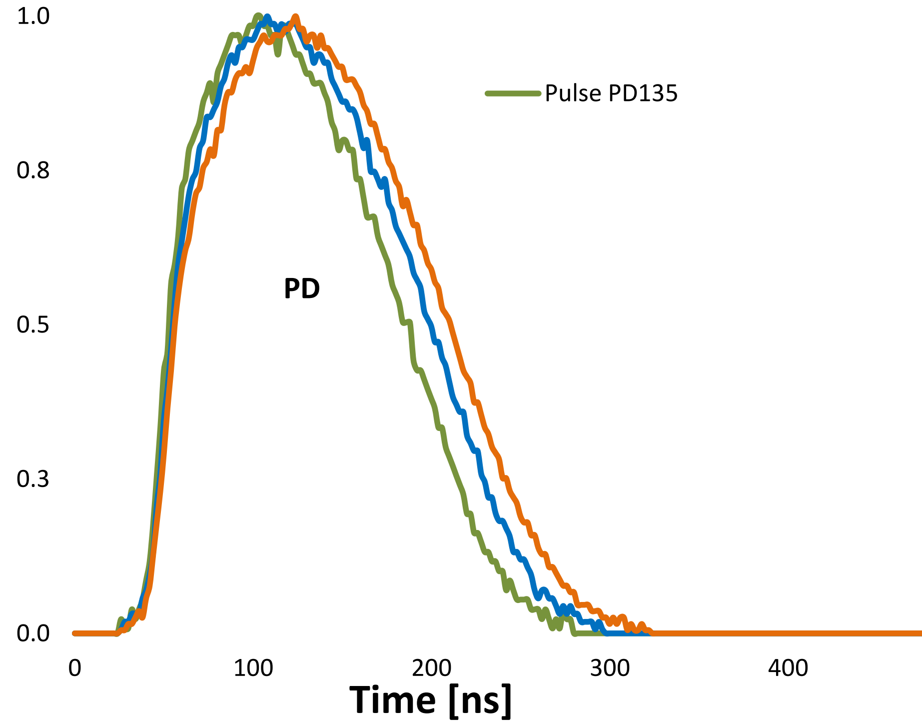
Thermal and phase change simulation

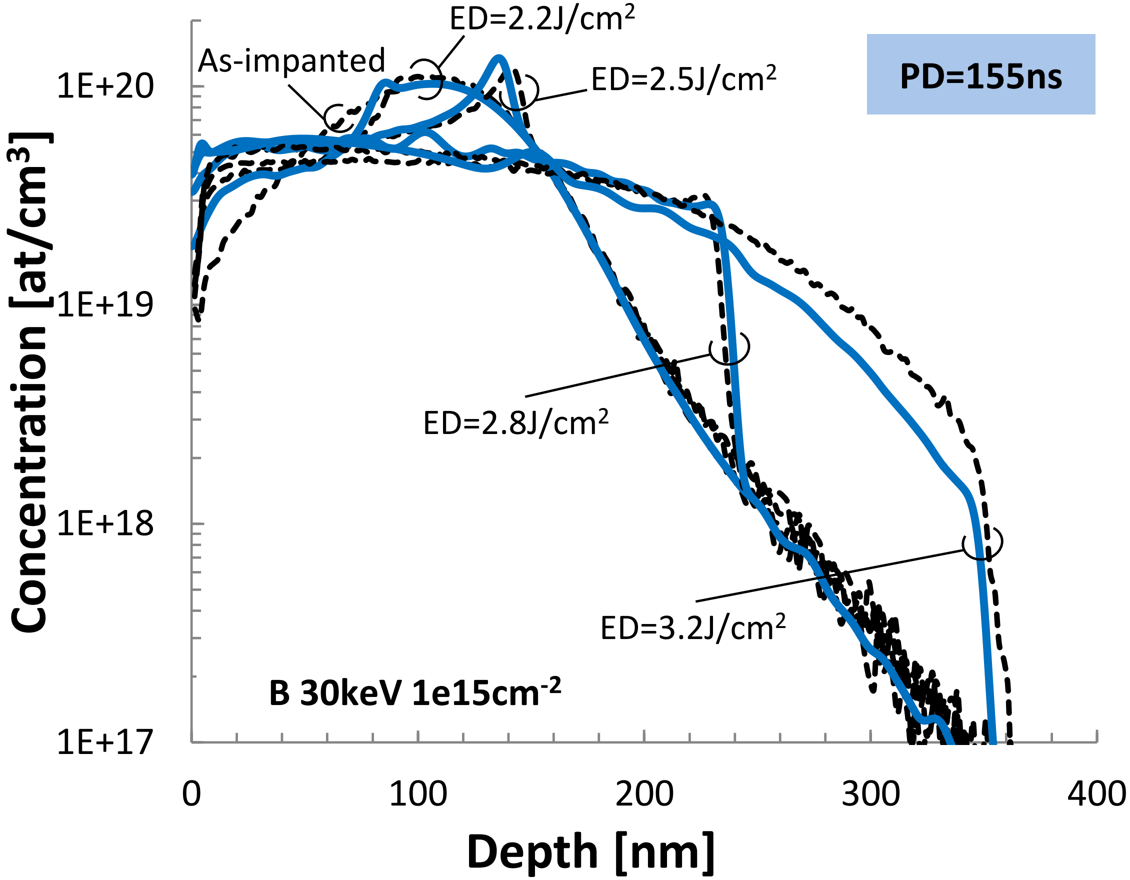




- **Model fit very well the experimental data**
  - Accuracy: $R^2 > 95\%$

Dopant distribution simulation

- **Good simulation of LTA junction formation**
- **Good agreement between simulation and experience**
- **Model accuracy: $R^2 > 90\%$**



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CONCLUSIONS

- **Objective**
  - Linking tool parameters to process
  - Model validation

- **Conclusions**
  - Good agreement between model and experiences in case of LTA time shift
    - ⇨ Melt Depth
  - Good simulation of LTA junction formation
    - ⇨ Diffusion & segregation

- **Perspectives**
  - Tool for process integration
  - Extend to other dopants

THANK YOU FOR YOUR THE ATTENTION !