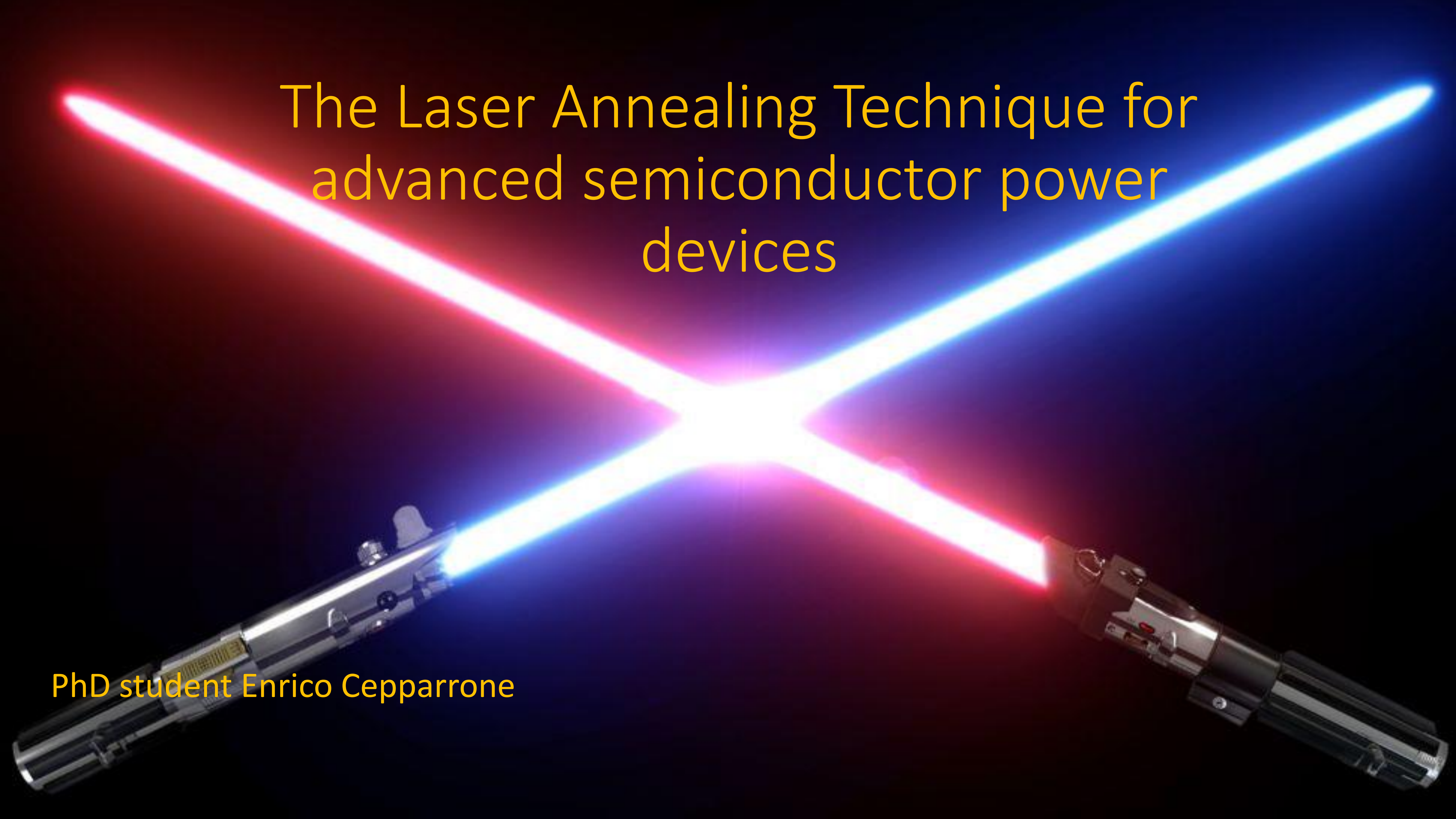


The Laser Annealing Technique for advanced semiconductor power devices

PhD student Enrico Cepparrone

Outline

- What is thin diode technology
- Thermal process. Critical point for this technology
- Simulation and validation of the model
- Experimental part
- Conclusion

Collaboration

This Phd thesis was carried out in collaboration with Vishay Semiconductors italiana S.P.A. a company specialized in the production of power electronic devices.

Vishay Intertechnology is a multinational company founded in 1962 by Dr. Felix Zandman and it is became one of the world’s largest manufacturers of discrete semiconductors and passive electronic components.

Collaboration

The project that lead this Phd provides to realize a new device combine the **Vishay technologies** with the

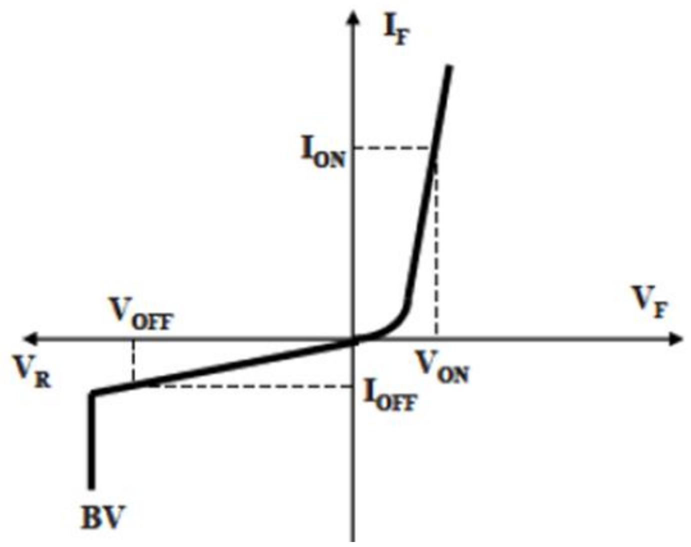
thin diode technologies

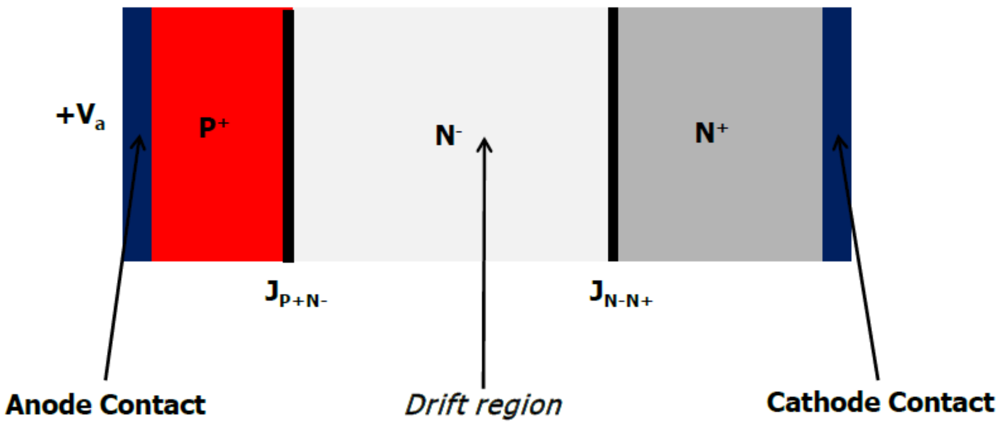
But what we are talking about?

We need to do a step behind….

PiN Diode Technologies

A diode is a semiconductor device that conducts current primarily in one direction; it has low resistance in one direction, and high resistance in the other. A semiconductor diode is a crystalline piece of semiconductor material with a p–n junction connected to two electrical terminals





PiN diode structure

A PIN diode is a diode with a wide, low-doped intrinsic semiconductor region between a p-type semiconductor and an n-type semiconductor region.

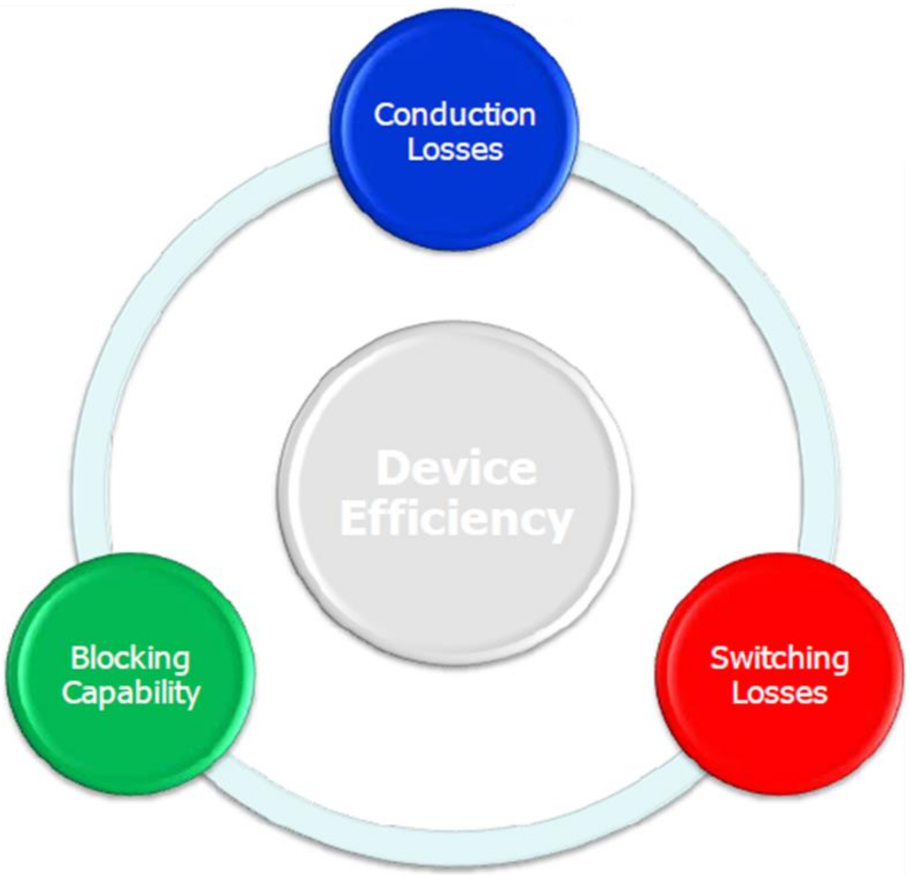
Main Diode Applications

- Server power supplies
- High end desktop power supplies
- Telecom power supplies
- Solar inverters
- Notebook adaptors
- Charging stations

Advantages of thin Diode technology

The **thin wafer technology**, applied to Power Diodes is expected to have an impact on the following parameters

- Device thermal resistance
- **Conduction and switching energy losses**
- Device robustness in dynamic transient conditions

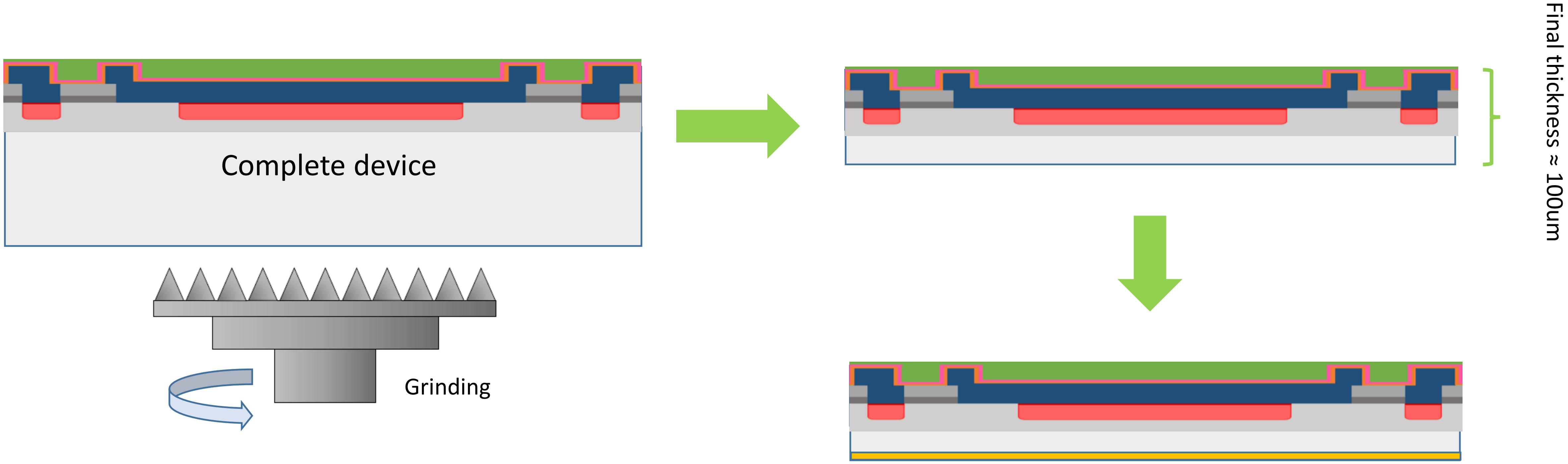


How thick are a “normal” and thick Diode?

Critical Issue

- Wafer handling after the thinning process
- Processing of the cathode region

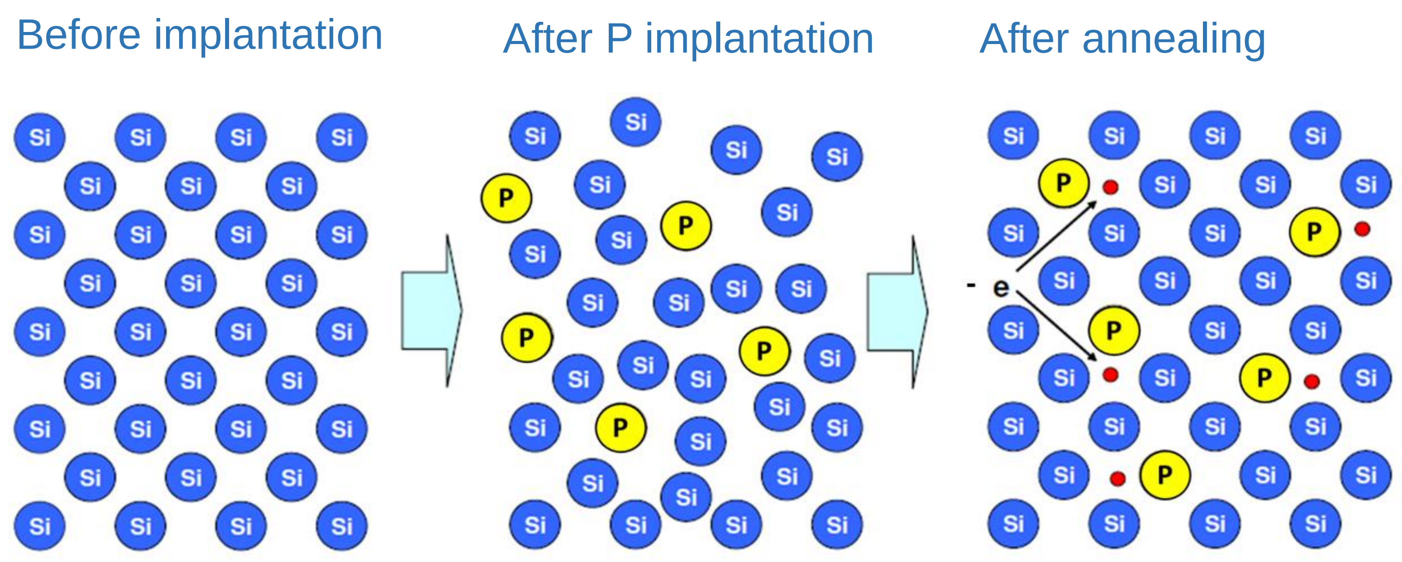
After the grinding process the diode reach the final thickness but still need to build the cathode



Cathode implantation

Cathode activation

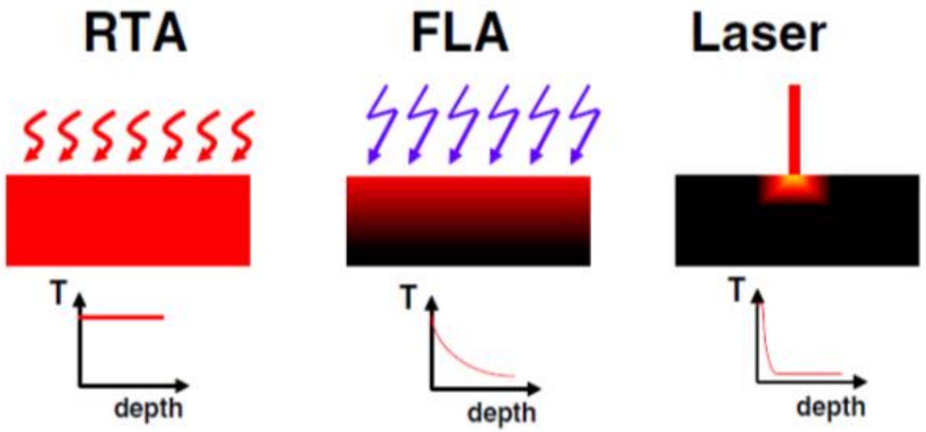
Nuclear stopping processes of ion implanted into Si are responsible for producing displacement damage. The types and amount of damage produced depend on implant species, energy, fluence, wafer temperature and orientation



Since the implanted species is not substitutional upon implantation and the crystal can be severely damaged during implantation, a post-implantation annealing step is necessary

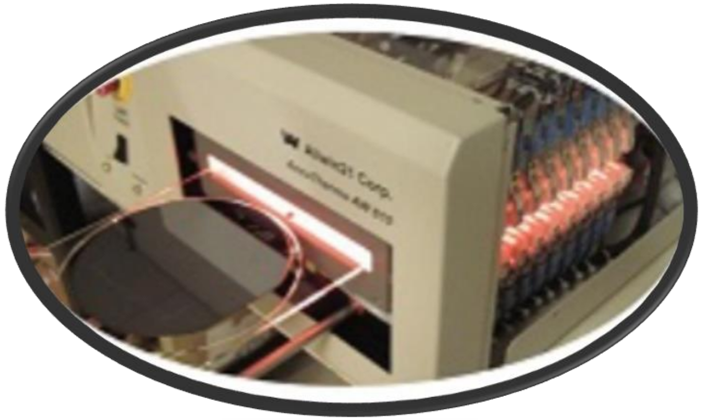
Annealing Process

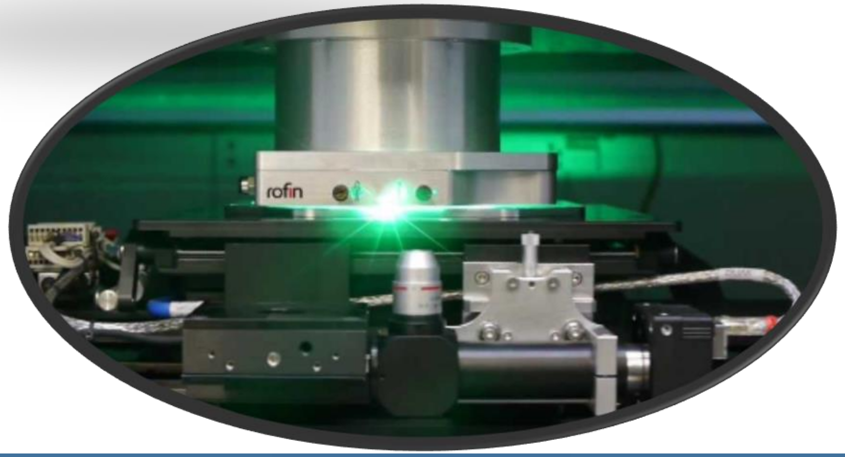
For the cathode activation is necessary to apply an annealing process able to reach very high temperature, while not damaging the front side metallic structures



backside	hot	cold	at RT
annealing times	1 – 100 s	100 μs – 100 ms	1 – 1000 ns
light source	halogen lamps	Xe lamps	pulsed laser
spectrum	broad ~ 800 nm	broad ~ 400 nm	discrete lines
pattern effects	not significant	significant, but reduced	significant
operation mode	wafer by wafer	wafer by wafer	wafer scanning

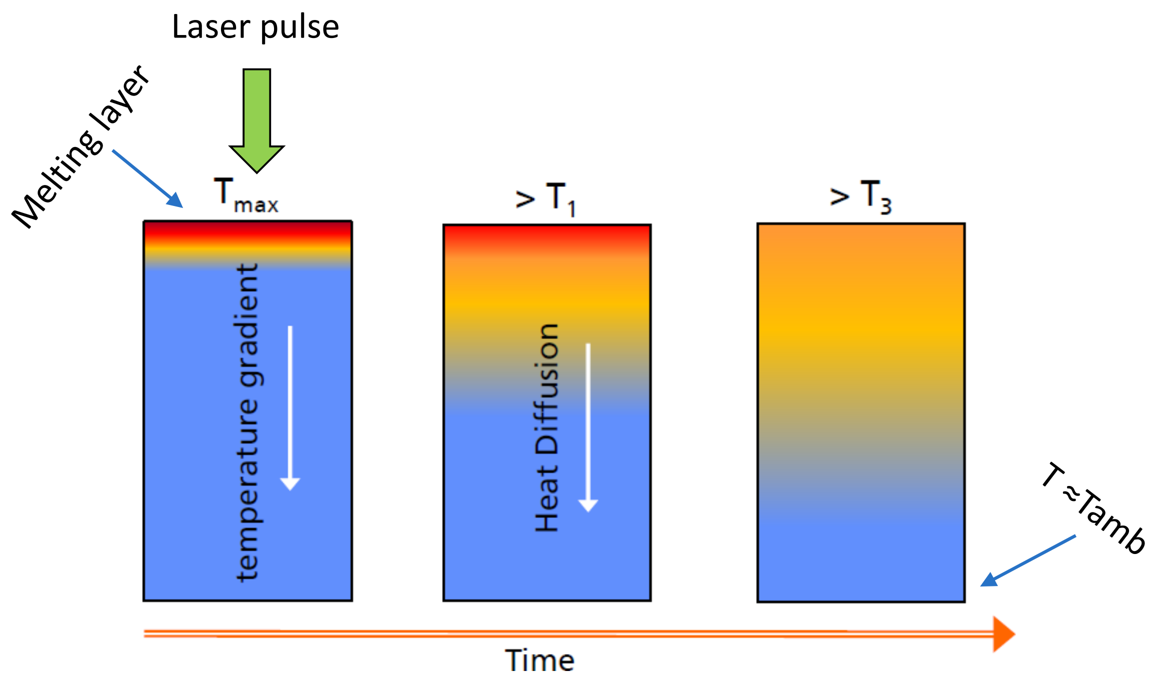
[S. Prucnal et all] "Doping by flash lamp annealing", Materials Science in Semiconductor Processing 62, 115–127 (2017).

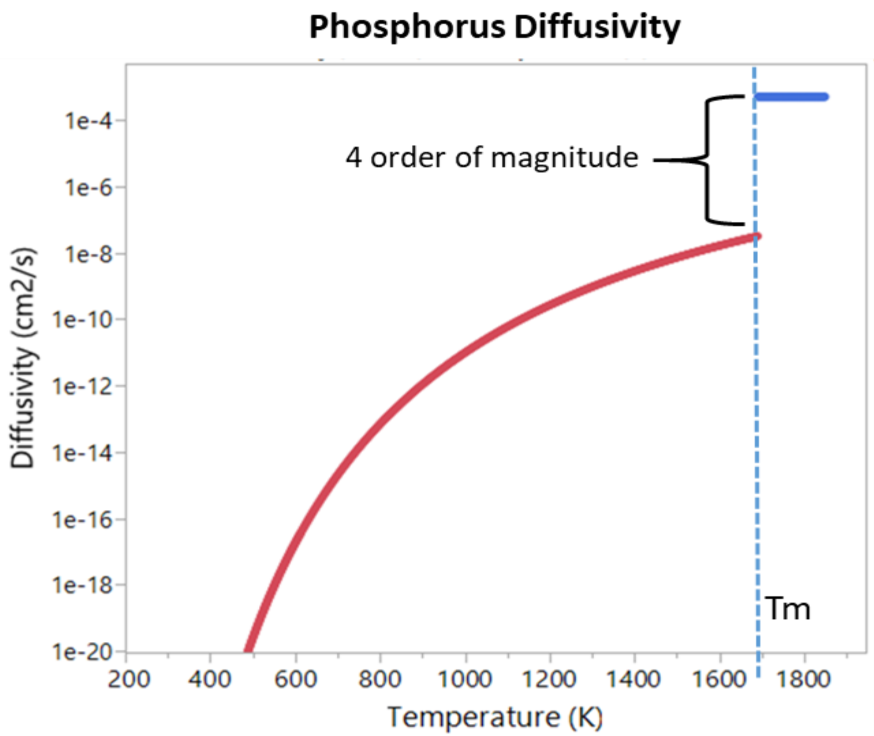




Laser Annealing

After a study which take into account the advantages and disadvantages of the main annealing technique and the linked literature is clear that the laser annealing is the only one that can guarantee the best condition for the thin diode cathode activation

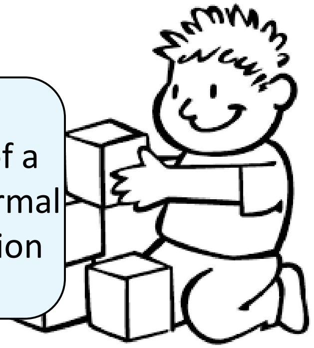




Looking the Phosphorus diffusion coefficient is clear that to have a good diffusion (and activation) in this time scale the material should be reach the melting state

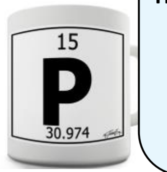
Laser Annealing Activities

Study and Implementation of a 1D model to simulate the thermal profile and the phase transition

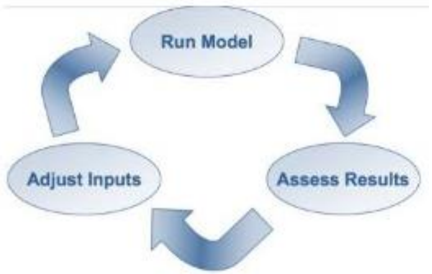


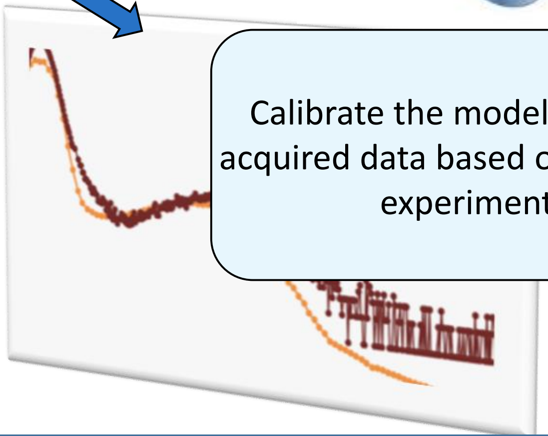
Need to to acquire

- Final roughness of our process before the implantation
- Melting depth by experimental data
- Physical behavior of the Phosphorus in the Silicon during laser process



Insert the dopant atom to study the diffusion and activation of the Phosphorus





Calibrate the model with the acquired data based on the laser experiment

Other objectives

- Implement a study of the final surface roughness after annealing
- Study how the annealing parameter are related with the electrical parameter of the devices
- Study how the laser process can be used to enhanced the device performances

Model Equation

Model based on the **PHASE FIELD METHOD**

Space-time differential equations for two variables:

- Temperature T
- Phase field ϕ, which varies smoothly from -1 (liquid phase) to +1 (solid phase) across a thin (few nm) diffusive interface region .

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

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

S: Experiment source term

$$-\nu \cdot (\varphi + 1) \cdot \theta[T > (T_M + dT)]$$

Nucleation term

Si thermal coefficients (available from literature)

- ✓ C_p: heat capacity
- ✓ K: heat conductivity
- ✓ L_{fus}: latent heat of fusion
- ✓ T_M: melting temperature
- ✓ ρ: density

Parametrization

- τ: atomic attachment time at the interface (ps)
- λ: coupling between phase and diffusion fields
- W: diffusive interface region thickness (nm)

Phase field

The phase field approach has its roots in statistical physics.
In particular, a new thermodynamic variable is introduced, the phase field ϕ(x,t), which is associated with the phase of the system as a function of the time and space and varies smoothly from one value in the liquid to another value in the solid across a spatially diffusive interface region of thickness

the Helmholtz free energy is a functional of the phase field and its gradient in the following form:

$$\mathcal{F}(\varphi,\ldots) = \int_{\Omega} \left[f(\varphi,\ldots) + \frac{1}{2}\epsilon^2 (\nabla\varphi)^2 + \cdots \right] d\Omega,$$

where Ω is the system domain and f (φ, . . .) the Helmholtz free energy density.

the basic equations of the phase-field model are:

$$\tau(\mathbf{n})\frac{\partial\varphi}{\partial t} = -\frac{\delta\mathcal{F}}{\delta\varphi} \qquad \frac{\partial U}{\partial t} = \frac{D}{b\lambda}\nabla^2\frac{\delta\mathcal{F}}{\delta U}$$

Where U is the dimensionless enthalpy, *τ* is the characteristic time of attachment of atoms at the interface, *D* the thermal diffusivity, *λ* is a dimensionless parameter and *b* a constant

Phase field

the Helmholtz free energy can be expressed in the following form:

$$F(\varphi, \lambda u) = f(\varphi) + \lambda g(\varphi) u \longrightarrow F(\phi, \lambda u) = -\frac{\phi^2}{2} + \frac{\phi^4}{4} + \lambda\left(\phi - \frac{2\phi^3}{3} + \frac{\phi^5}{5}\right)\left[\frac{Cp(T - T_m)}{L}\right]$$

This is a function that has the form of a double-well potential where the relative height of the two minima is temperature dependent

reformulating the fundamental equations of the phase field method with this functional that describes the Helmholtz free energy we obtained:

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

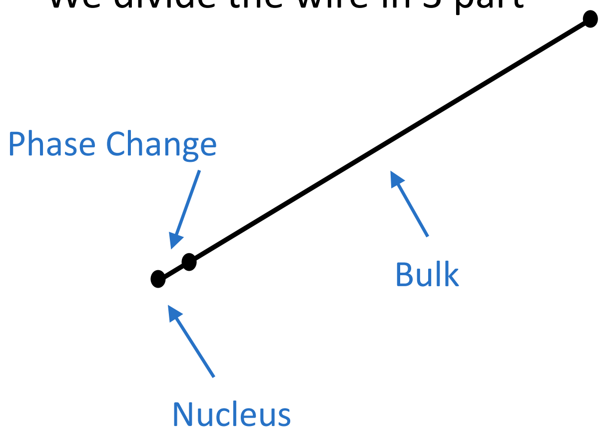
$$\rho c_p \frac{\partial T}{\partial t} - \nabla^2 (KT) = \frac{\rho L_{fus}}{2} \frac{15}{8} \left(\varphi^2 - 1\right) \frac{\partial \varphi}{\partial t} + S(x, t)$$

Model Validation

- We based ourselves on work of *Fisicaro, G. & La Magna, A. "Modeling of laser annealing" J Comput Electron (2014)*
- We used their parameter for the laser and the silicon

For this model we simulate the irradiation of a silicon wire at the tip

We divide the wire in 3 part



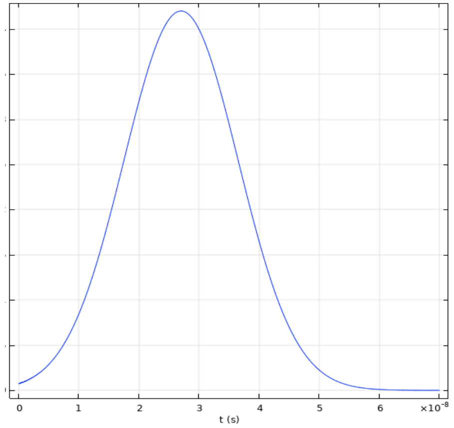
Time shape

Reflectivity

Source Term: $$S(x,t) = p(t) * I(1-R)\alpha e^{-\alpha y}$$

Absorption coefficient

Energy density (J/m^2)



The space and time modelling is a Gaussian shape

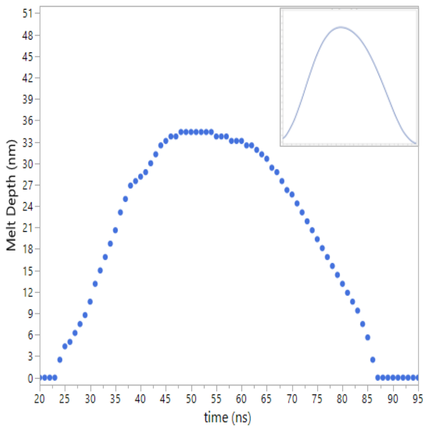
$$p(t) = \frac{1}{\sqrt{2 * \pi * st^2}} e^{-\frac{(t-pt)^2}{2st^2}}$$

- Nucleus, we insert the trigger equation where the melt phase can nucleate
- Phase Change, we insert the complete phase change equation
- Bulk, we insert a simple form of the phase change equation

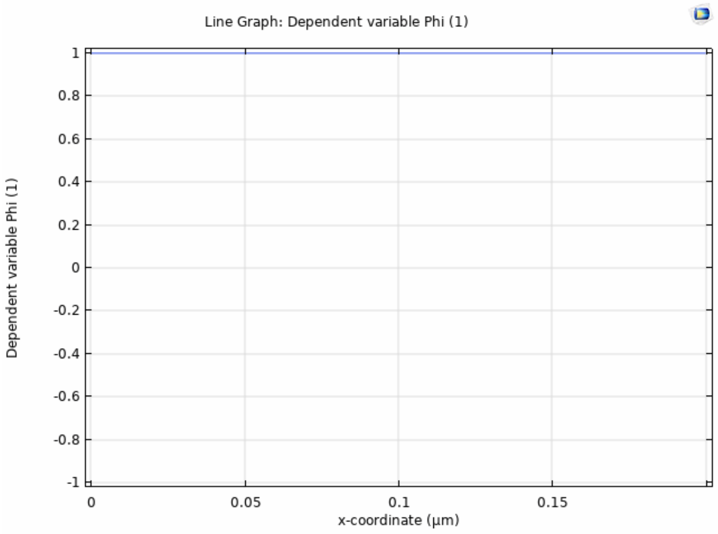
Model Validation

Tracing the change of sign of the phase within the material it is possible to follow the melt depth in the time

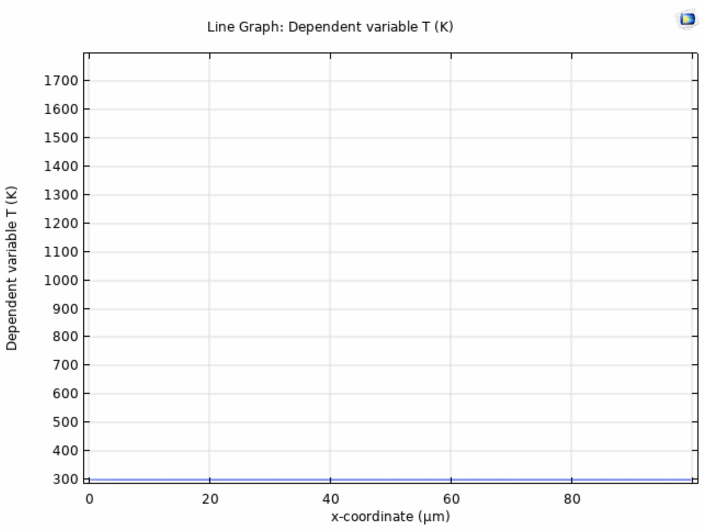
Each point corresponds to a change of sign of the Phase



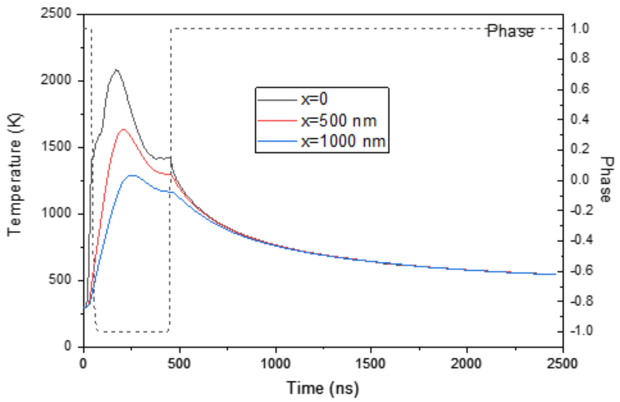
Phase variation in the material



Temperature variation in the material



Surface temperature



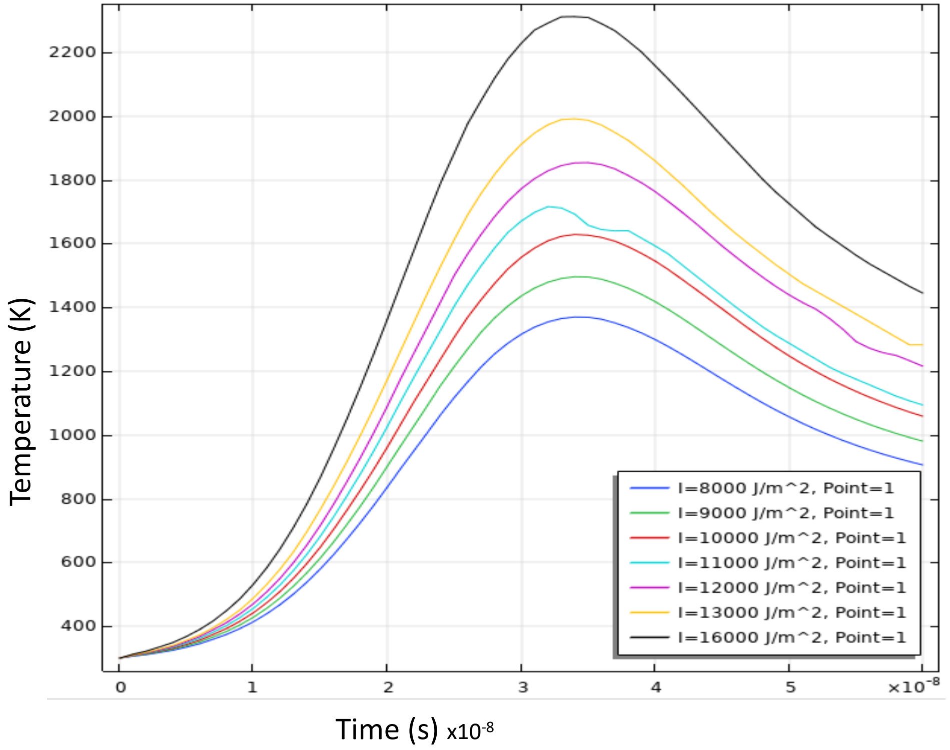
- We based ourselves on work of *Fisicaro, G. & La Magna, A. “Modeling of laser annealing” J Comput Electron (2014)*
- We used their parameter for the laser and the silicon

Model Validation

Temperature evolution at the surface with different laser fluence:
Comparison with the literature (Dairif 2008)

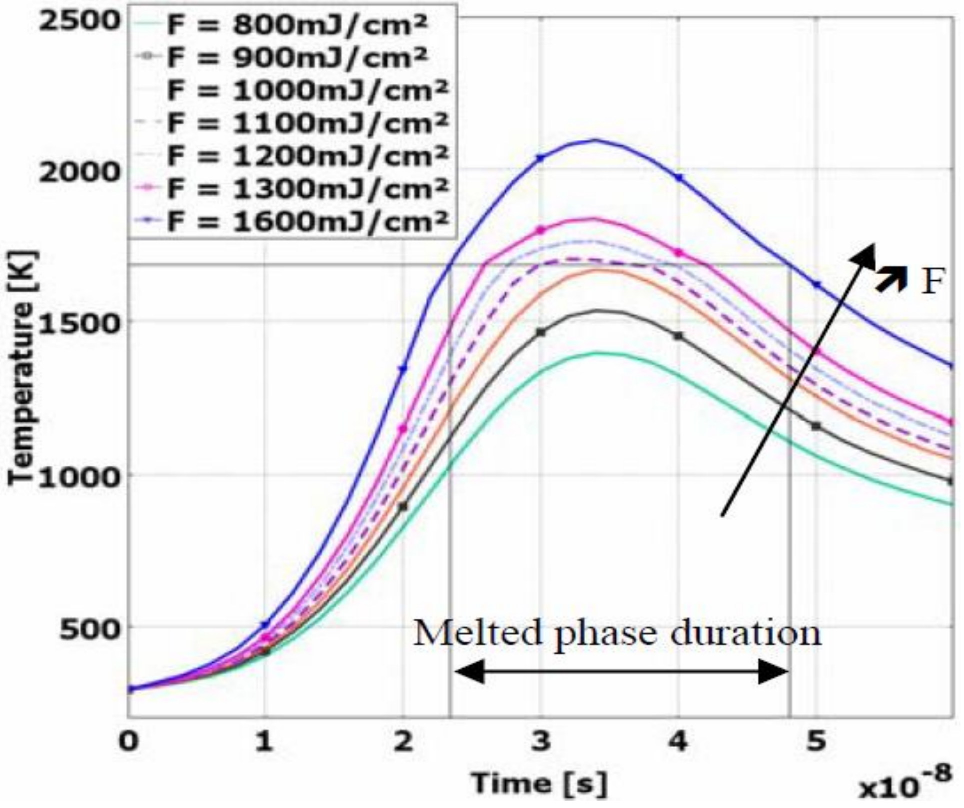
$$\tau\frac{\partial\varphi}{\partial t} = W^2\nabla^2\varphi - \varphi\left(\varphi^2-1\right) - \lambda\frac{c_p}{L_{fus}}\left(T-T_M\right)\left(\varphi^2-1\right)^2$$

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



For this first validation we used the same parameter of the paper, but using the phase field equation

$$\rho c_p\frac{\partial T\left(\mathbf{r},t\right)}{\partial t} = \nabla\cdot\left[K\,\nabla T\left(\mathbf{r},t\right)\right] + S\left(\mathbf{r},t\right)$$

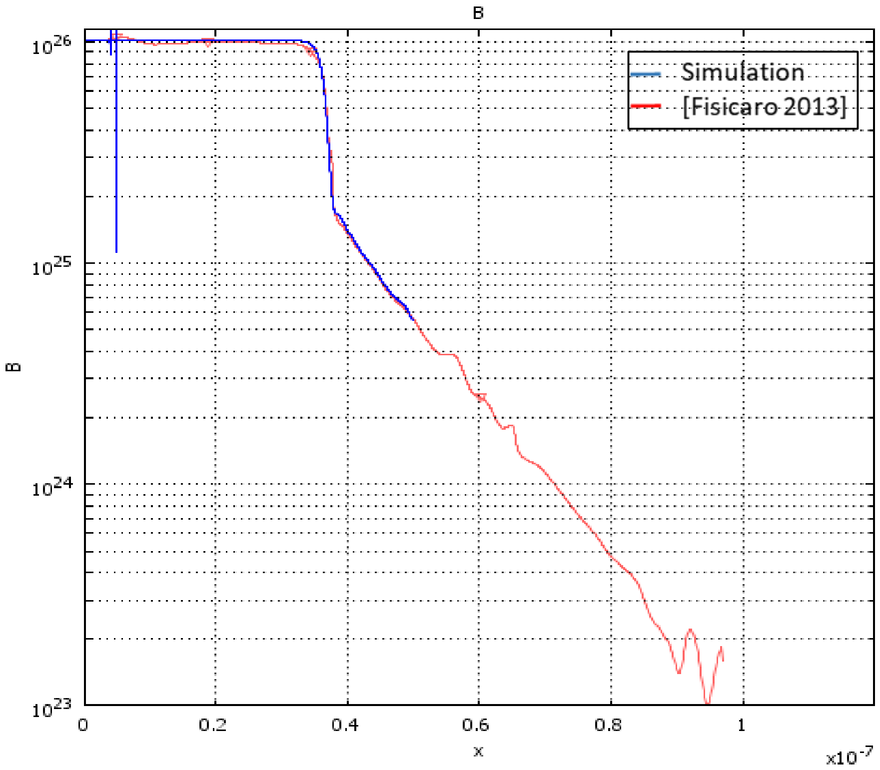


Numerical Simulation of Si Nanosecond Laser Annealing by COMSOL Multiphysics
M. Darif*, N. Semmar, GREMI-UMR6606, CNRS-Université d'Orléans, (2008)

Boron Diffusion

The first approach was to consider a pure Fick diffusion

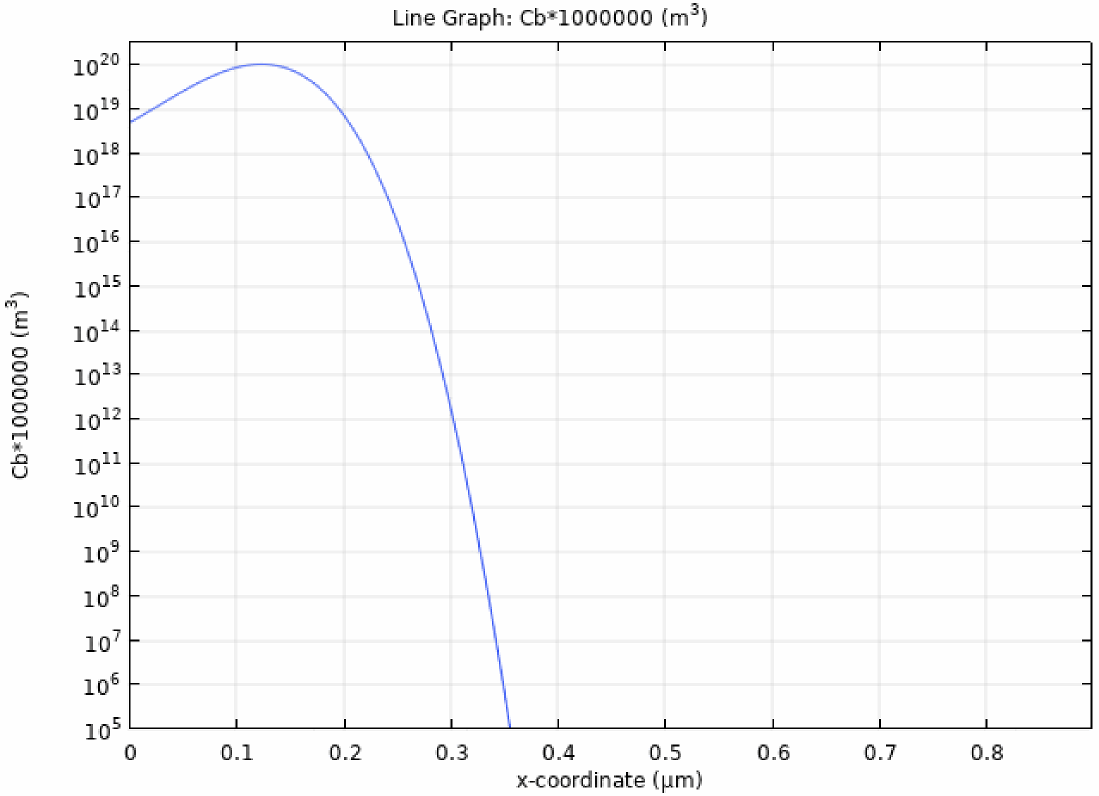
$$\frac{\partial C_B}{\partial t} = \nabla[D_B(T, \Phi)\nabla C_B],$$



Boron profile after LTA, (blue solid line) calculated by solving the Fick equation in comparison with the simulation result from Fisicaro et all, “Anomalous Impurity Segregation and Local Bonding Fluctuation in l-Si”, PRL 110, 117801 (2013)

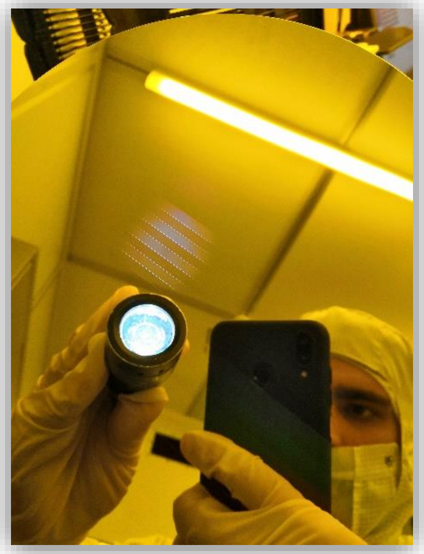
The calculus was performed by solving the system of the three equations (T, φ, C_B)

The boron diffuse fast during the melting state of the material



Fraunhofer Experiments

Fraunhofer
ISIT

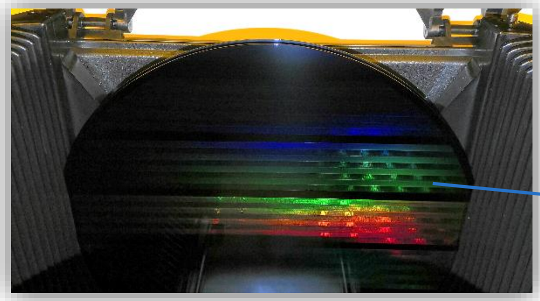


In the thin diode project is involved also the Fraunhofer Institute of Itzehoe which make available some technologies and knowledge

In this period I collaborate with the Fraunhofer engineers and also Hans Juergen Schliwinski an Laser annealing expertise

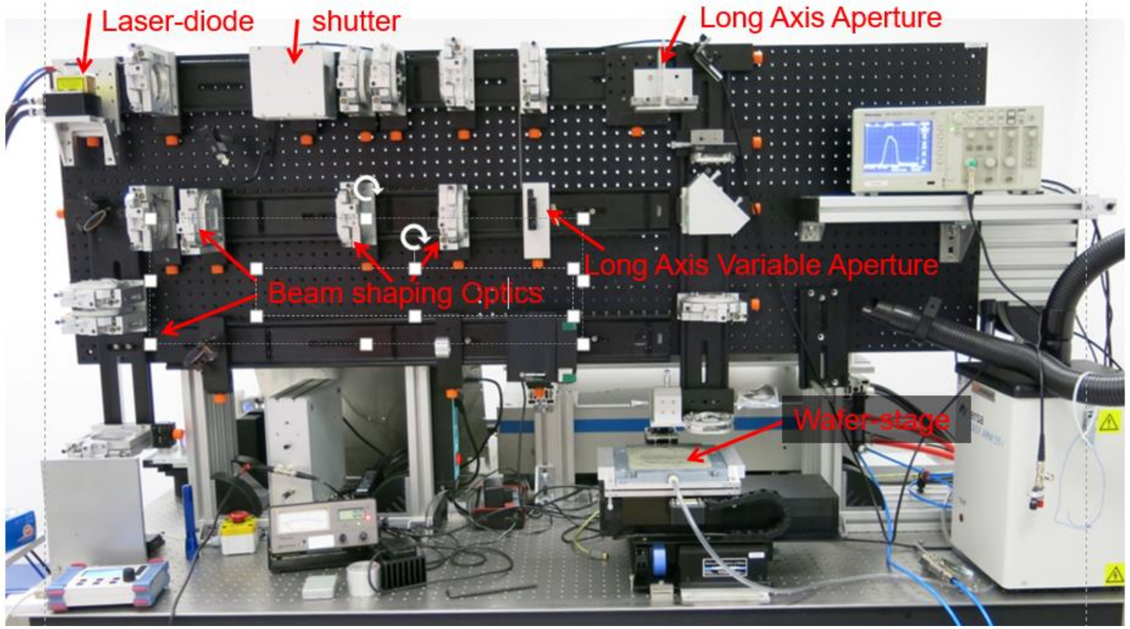
Laser Annealing tool

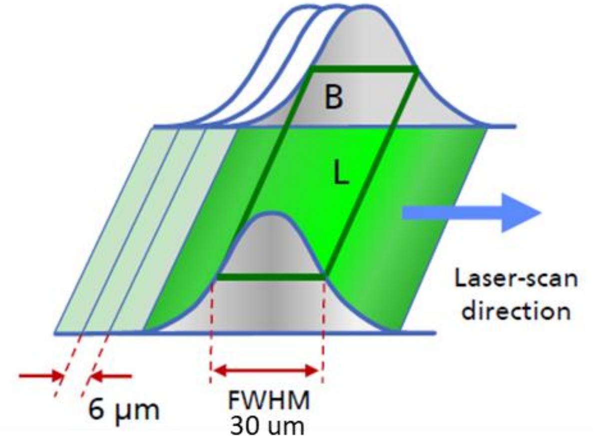
The laser annealing instrument which is used into the German period is the ASAMA laser developed by INNOVAVENT together with Jenoptik Laser GmbH, a frequency-doubled solid state laser

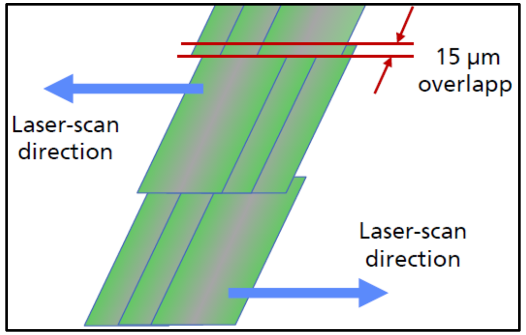


Laser scanning line

Wavelength	515 nm
Variable pulse duration	500 - 1200 ns
pulse frequency	10 kHz
Energy density	variable, up to 4 J/cm2
Laser scan speed	30-150 mm/s
Beam shape on the wafer	line

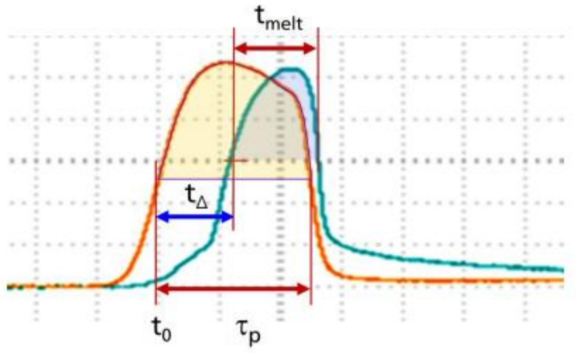






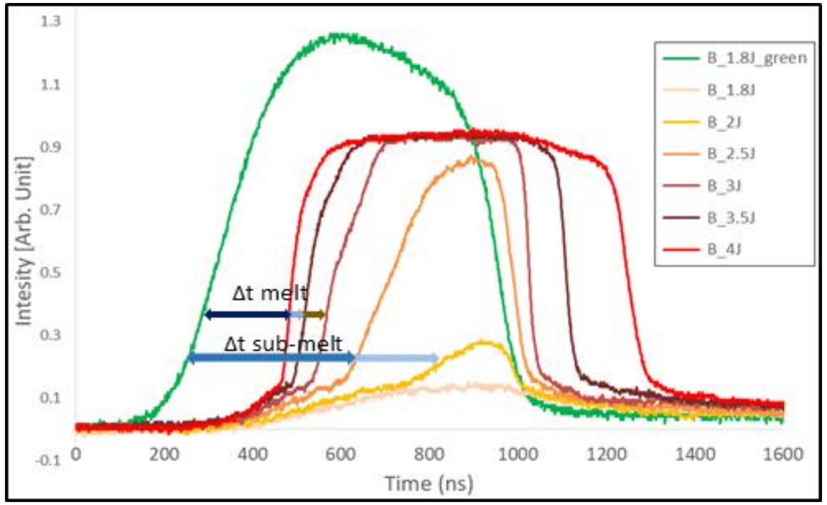
Fraunhofer Experiments Outcomes

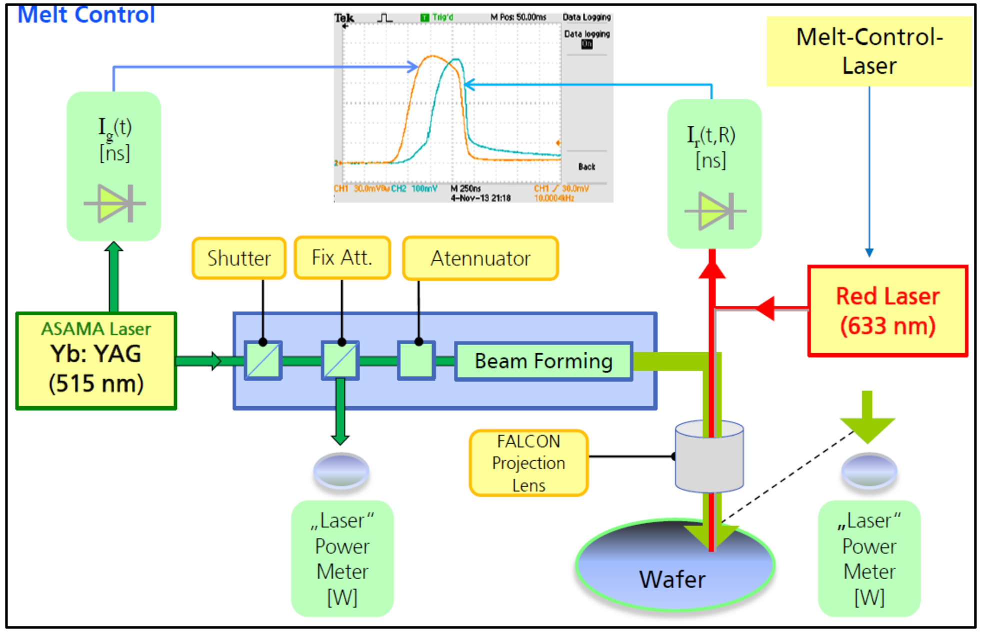
Fraunhofer ISIT

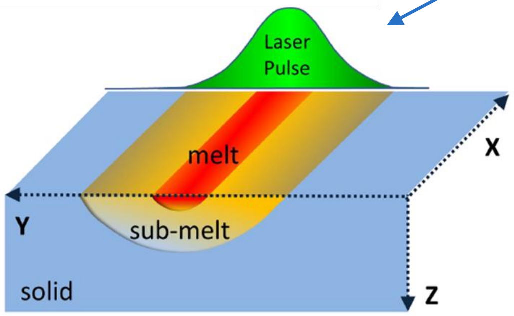


Surface melting signal

To collect the surface melting signal the system use a second laser with different wavelength and low power. It is pulsed together the green laser







The melting curves was taken:

- At different laser energies
- At different scanning speed
- On Implanted and pure silicon

Fraunhofer Experiments Outcomes

Fraunhofer ISIT

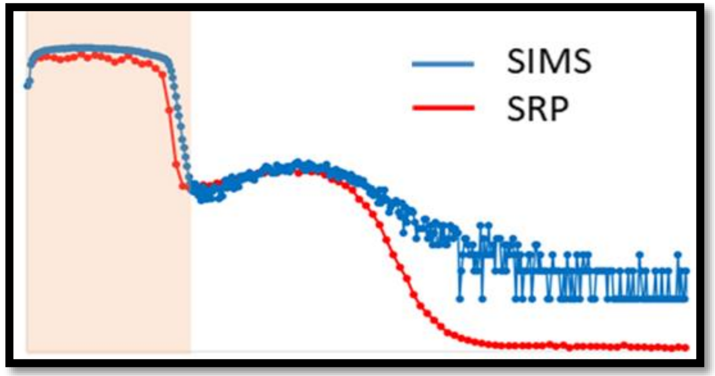
SIMS and SRP Analysis

Thanks to the collaboration with Vishay and the help of the failure analysis Vishay people it was possible to perform some SRP analysis during my period in Germany

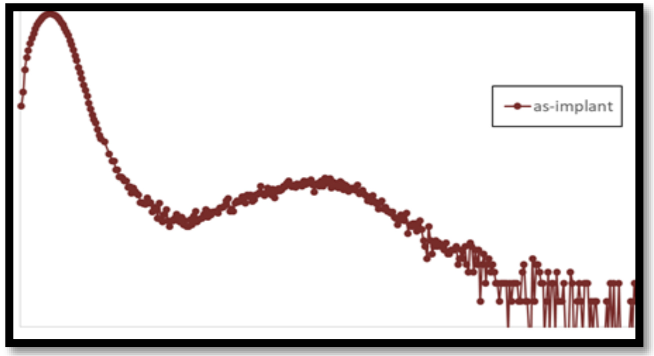
SIMS (Secondary Ion Mass Spectrometry) information:
Spatial distribution of the dopant

SRP (Spreading Resistance Profiling) information:
Spatial distribution of the **activated** dopant

SIMS/SRP comparison



Between the SIMS/SRP ratio is possible to find the % of activation of the dopant



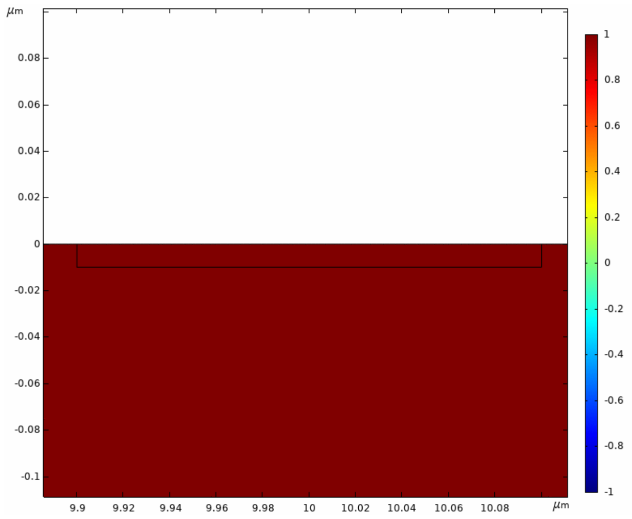
The SIMS is a useful to detect the correct dose of dopant implanted in the silicon

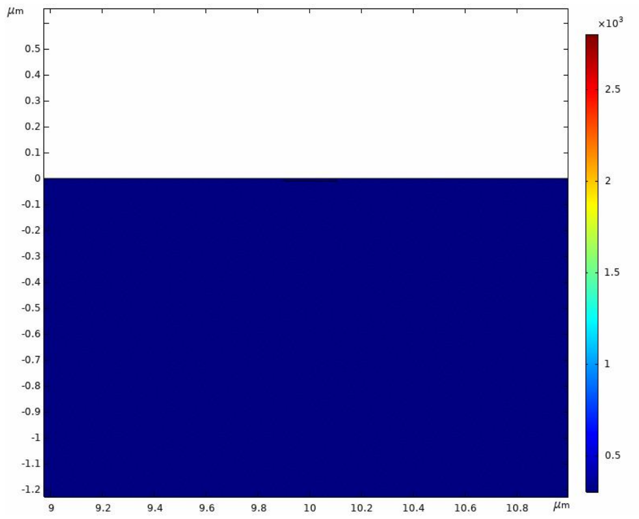
SRP sample

2D Model

State of the art:

- Implementation of a 2D model,
  - Pure intrinsic silicon
  - Constant optical parameters
  - Extension of the integration domain :
- Source: laser wavelength= 515 nm
  - One single laser shot
  - Gaussian time evolution with FWHM = 70 ns
  - Gaussian spatial profile with FWHM = 1 um
  - Energy density = 2 J/cm^2





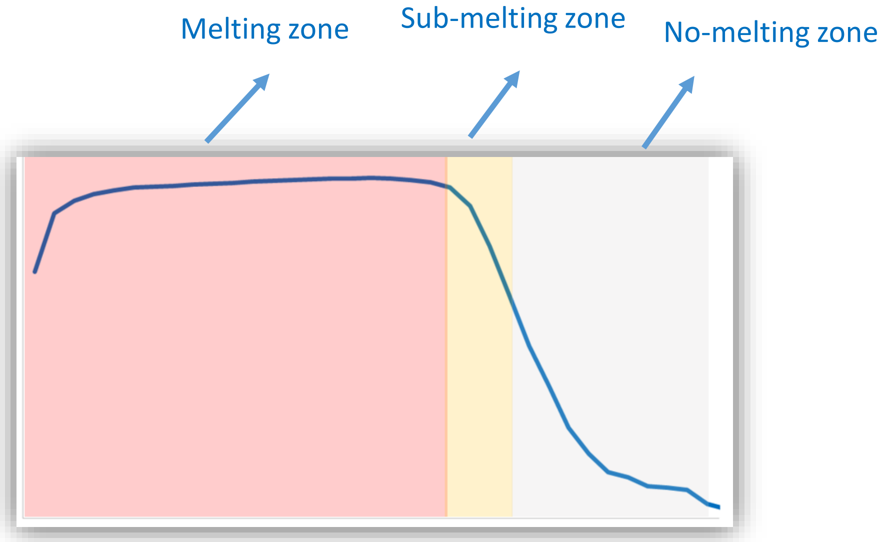
Problems

- Mesh grid very tight
- Long computational times
- Convergence issues

Actions plan

1. Reduction of the integration domain to the active region of the energy absorption (few µm)
2. Improvement of the numerical algorithm (support of COMSOL)
3. Definition of the laser source
4. Calibration of the model through the comparison with experiments in order to define the optimal parameters

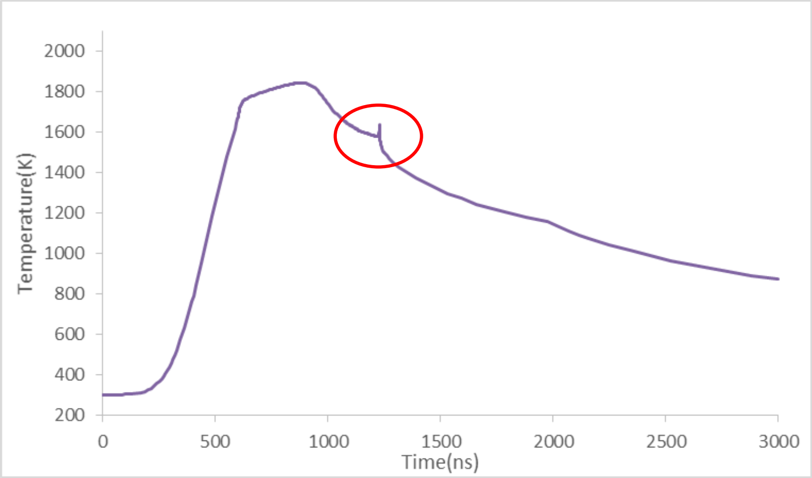
First Calibration data



- By **SIMS analysis** is possible to reach the **melting depth** of the silicon with no high accuracy but enough for a first calibration.

- By **Reflectivity melting signal** is possible to reach the **melting time of the surface** and to have a comparison with the surface reflectivity data of the simulation

- Another data take into account to verify the quality of the simulation is the **changing phase temperature** during the solidification. In correspondence of the solidification, when the phase parameter goes to negative to positive, occurs a short rise in temperature and based on the initial temperature of the rising is possible to verify if the phase transition occurs at the correct temperature

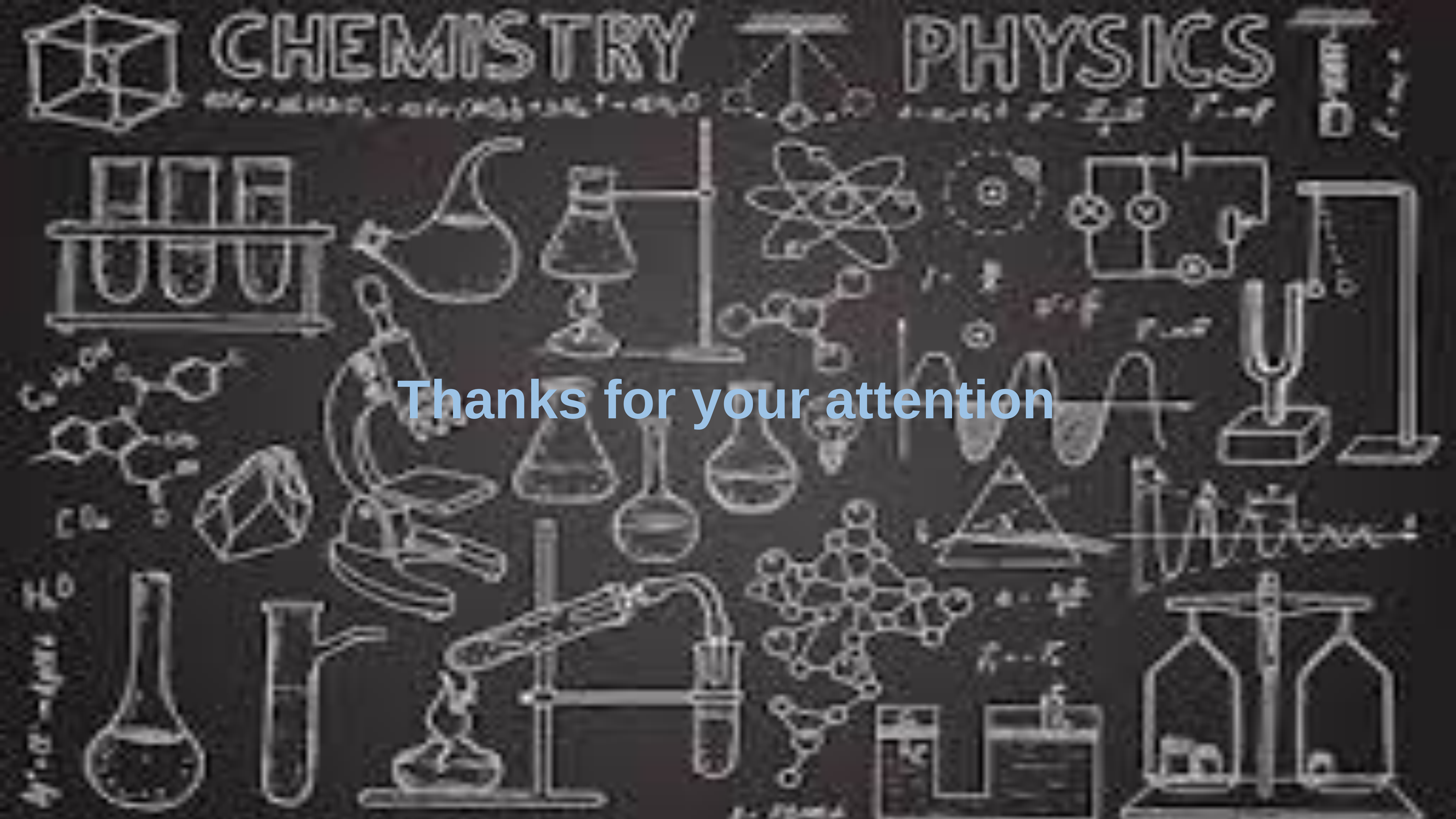


Next Experimental Step

- A second Laser experiment (with SRP and SIMS analysis) will be perform varying the laser parameters and the implantation dose

- Due to quarantine we interrupt the TEM analysis useful to get information about the melting depth and the lattice damage due to the implantation

- A optical analysis of the annealing surface in order to evaluate the final surface and study if this could be cause of issue in the metallization adhesion



Thanks for your attention