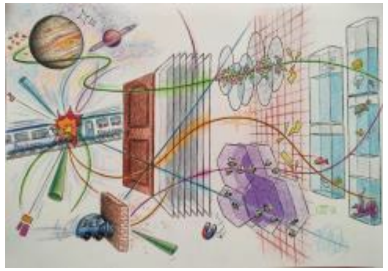


RD50 Common Project

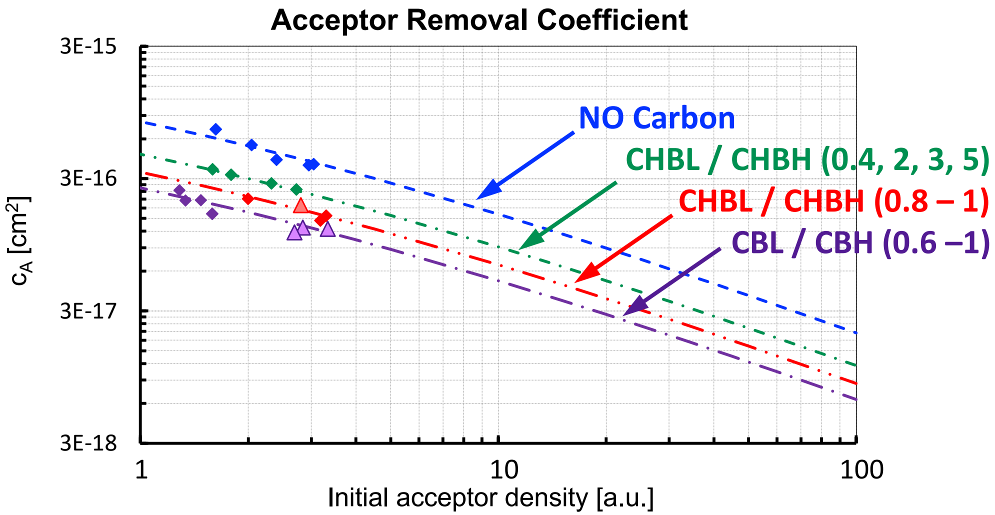
Partial Activation of Boron to enhance the radiation tolerance of the gain implant

PAB Activity Update

V. Sola for the PAB team

The Idea

Investigate the partial activation of the boron atoms implanted in the LGAD gain layer to enhance the tolerance to radiation



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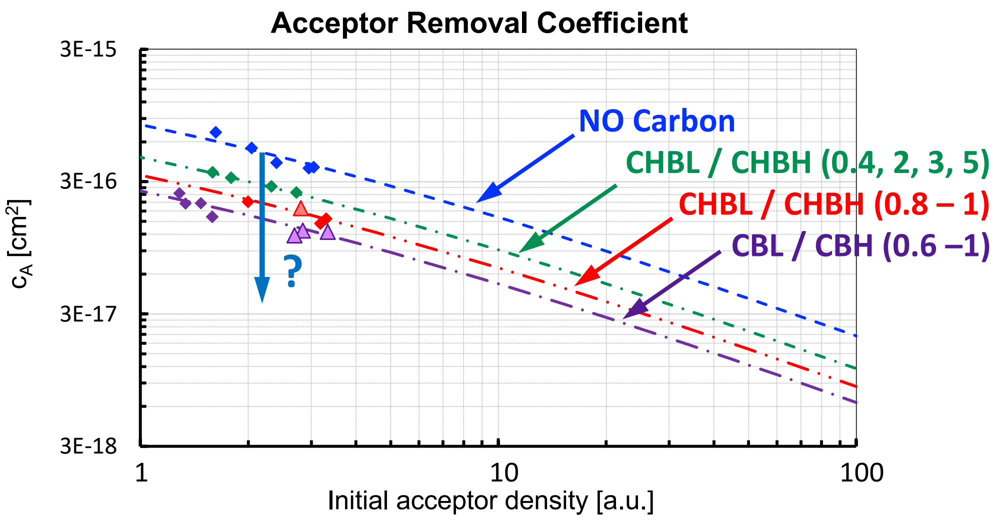
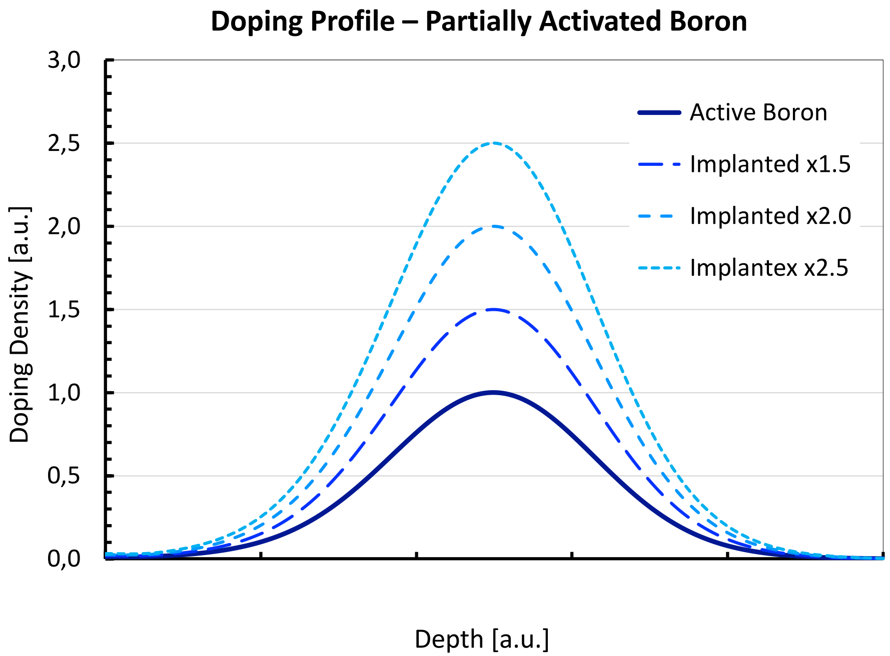




The Motivation

If the reactions

$B_s + Si_i \rightarrow B_i$

$B_i + O_i \rightarrow B_iO_i$

are main players in the acceptor removal process, increasing the fraction of B_i already present in the lattice, may protect B_s from removal

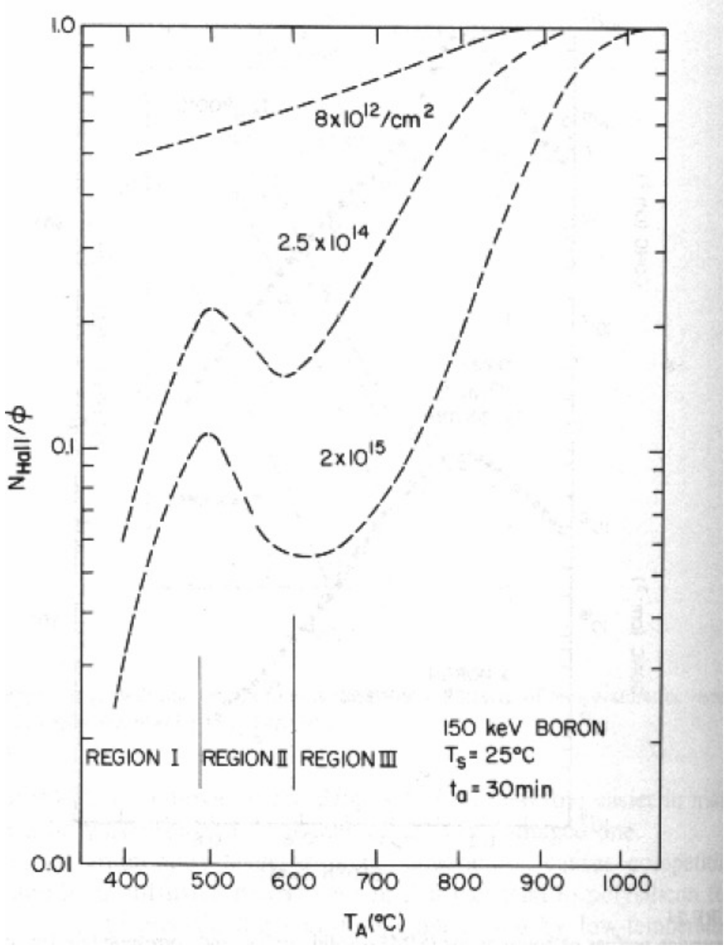
It is possible that there is an interval in the fraction of active / implanted boron which minimise the acceptor removal and it needs to be carefully investigated

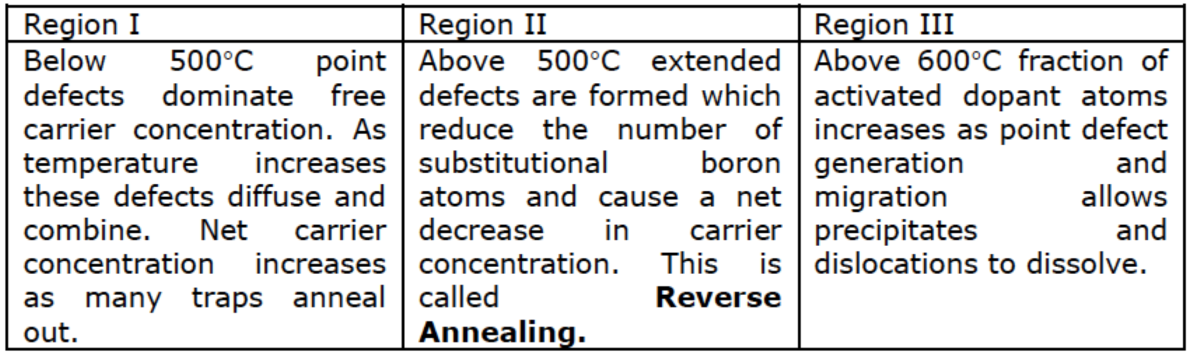
Latest HPK results

I. Velkovska et al., Radiation hardness studies of Half-Activated-Boron LGADs, Last (43rd) RD50 Workshop on Radiation Hard Semiconductor Devices for Very High Luminosity Colliders, CERN, 2023
indico.cern.ch/event/1334364/contributions/5672083

Partial Activation of Boron

Isochronal annealing of boron





Region I	Region II	Region III
Below 500°C point defects dominate free carrier concentration. As temperature increases these defects diffuse and combine. Net carrier concentration increases as many traps anneal out.	Above 500°C extended defects are formed which reduce the number of substitutional boron atoms and cause a net decrease in carrier concentration. This is called **Reverse Annealing.**	Above 600°C fraction of activated dopant atoms increases as point defect generation and migration allows precipitates and dislocations to dissolve.

T.E. Seidel and A.U. Mac Rae, The isothermal annealing of boron implanted silicon, Radiation Effects 7 (1971) 1, doi:10.1080/00337577108232558

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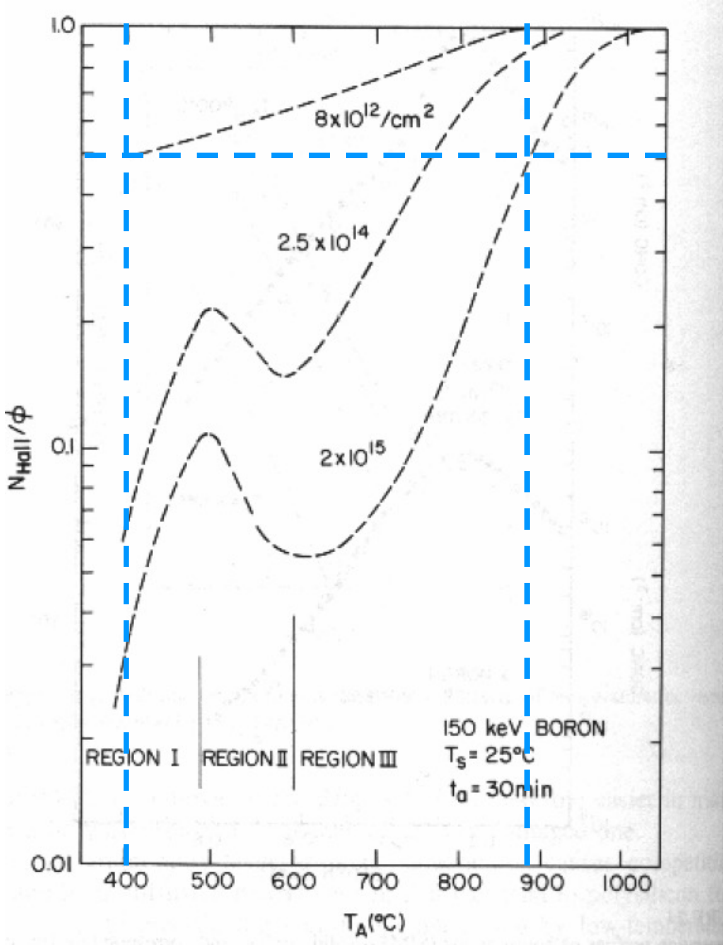

8E12/cm^2 is similar to the dose of the gain layer implant

→ **In this case, the activated fraction ranges from 50% at T = 400ºC to 100% at ~ 900ºC**

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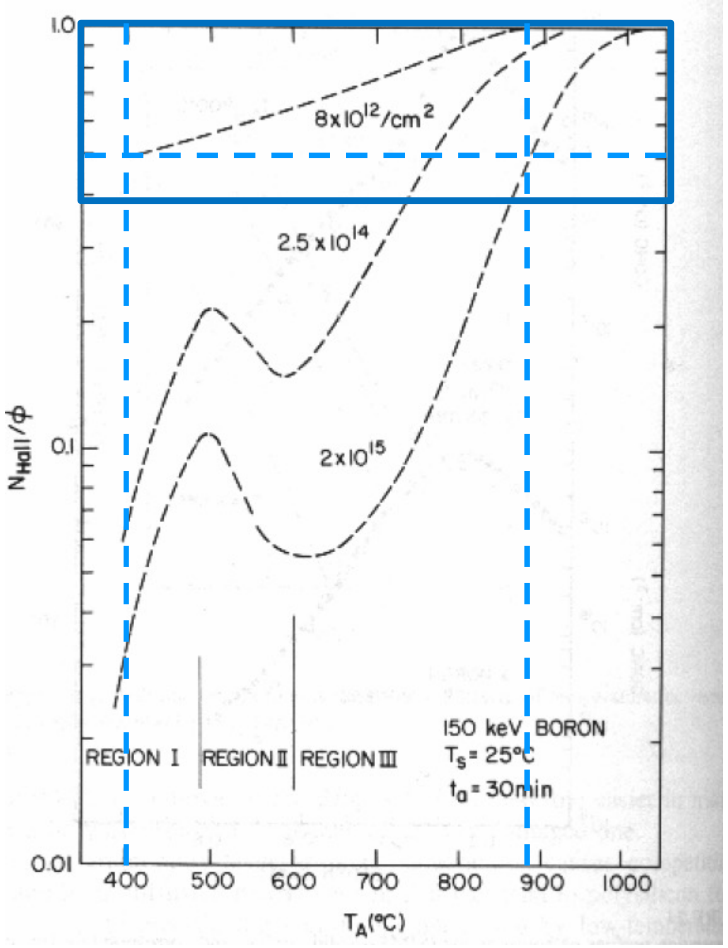

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Necessary to explore for LGADs doses by

- ▻ varying the activation T
- ▻ varying the activation t

T.E. Seidel and A.U. Mac Rae, The isothermal annealing of boron implanted silicon, Radiation Effects 7 (1971) 1, doi:10.1080/00337577108232558

List of Participants

INFN Torino	Coord. and sensor characterisation	V. Sola
CNM	Sensor production	G. Pellegrini
FBK	Sensor production	G. Paternoster
JSI	Sensor irradiation and characterisation	G. Kramberger
Helsinki Institute of Physics	Sensor irradiation and characterisation	J. E. Brücken
INFN Perugia	Sensor simulation and characterisation	F. Moscatelli
CERN	Sensor characterisation	M. Moll
University of Montenegro	Sensor characterisation	G. Medin
NIMP, Romania	Sensor characterisation	I. Pintilie
HEPHY, ÖAW, Wien	Sensor characterisation	T. Bergauer
Vilnius University	Sensor characterisation	T. Čeponis
Instituto de Física de Cantabria, CSIC	Sensor characterisation	I. Vila Álvarez

+ interest from SCIPP, UC Santa Cruz group – contact: S. Mazza

Project Cost

CNM wafer purchase	€ 2,000
CNM wafer processing (8 wafers)	€ 25,000
FBK wafer processing (8 wafers)	€ 25,000
Total cost of the project:	**€ 52,000**

For the sensor productions, masks already available from previous batches of LGAD sensors will be used, to save costs

For the CNM batch, a wafer purchase with the project funds is foreseen

For the FBK batch, the use of wafers already in-house is foreseen

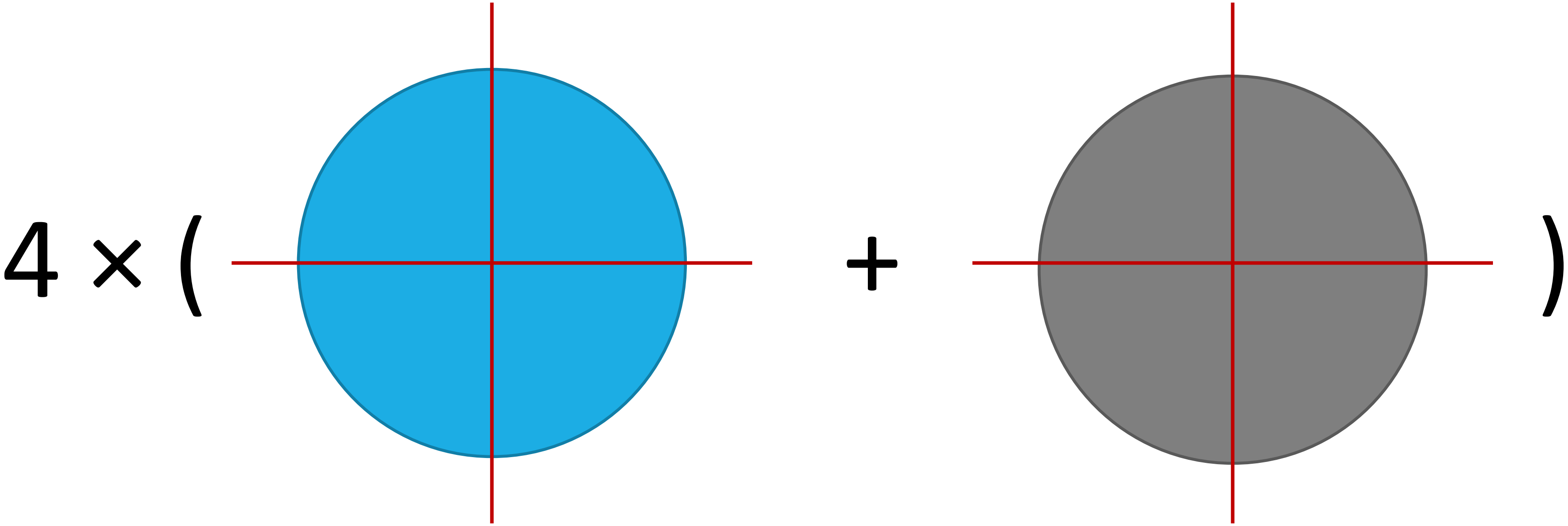
For the irradiation campaign, the EURO-LABS transnational access to the JSI facility will be requested, to cover the irradiation costs. All the irradiation costs not covered by the EURO-LABS consortium will be covered by the JSI group as an in-kind contribution

Original Proposal

Short loop runs to calibrate the boron activation process

CNM & FBK batches will consist of 8 wafers:

- ➢ 4 wafers with different implanted boron dose
- ➢ 4 wafers with same implanted boron dose + carbon
- ➢ each wafer will be cut in 4 parts that will receive different annealing



Test run - Looking for a partial activation point

Test run (Finished): looking for a partial activation point:

- **4** Wafer (standard high resistivity p-type) + **4** wafer (standard high resistivity n-type)
  - TOPSIL, FZ 100 mm, p-type (>10 kΩ·cm) + TOPSIL, FZ 100 mm, n-type (>10 kΩ·cm)
- Dopant implant (through a 365 Å screen oxide, no mask):

	Dose [at/cm^2]	Energy [keV]
P-type wafers (1-4)	5E12	480 (IBS)
N-type wafers (5-8)	5E12	480 (IBS)

- Thermal activation (**1** process per wafer):

	Furnace	Temp	Time
1-5	RTA	600 °C	60 sec
2-6	RTA	700 °C	60 sec
3-7	RTA	800 °C	60 sec
4-8	Tubular	600 °C	30 min

T might be a bit high, but we play also with time

- Wafers processed and diced (many samples per wafer)
- **Spreading Resistance Profile** analysis **on going** (expected before the end of the year):
  - If partial activation is observed, we can run SRP on irradiated samples

Our implant dose is even lower (5E12)
We can expect full activation at lower T

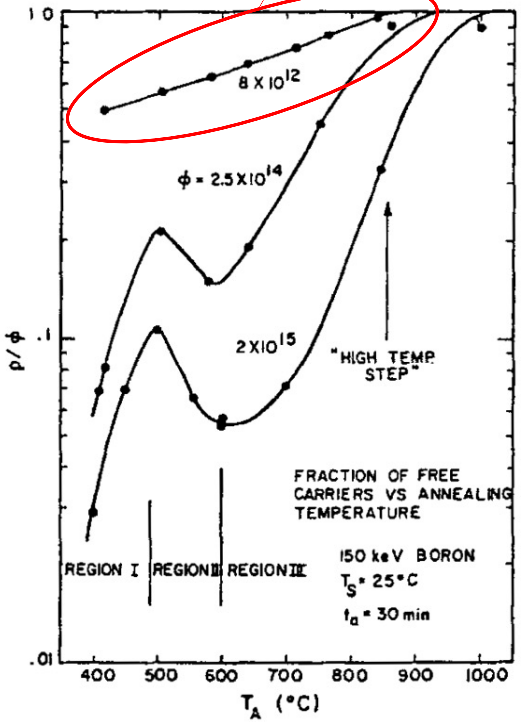


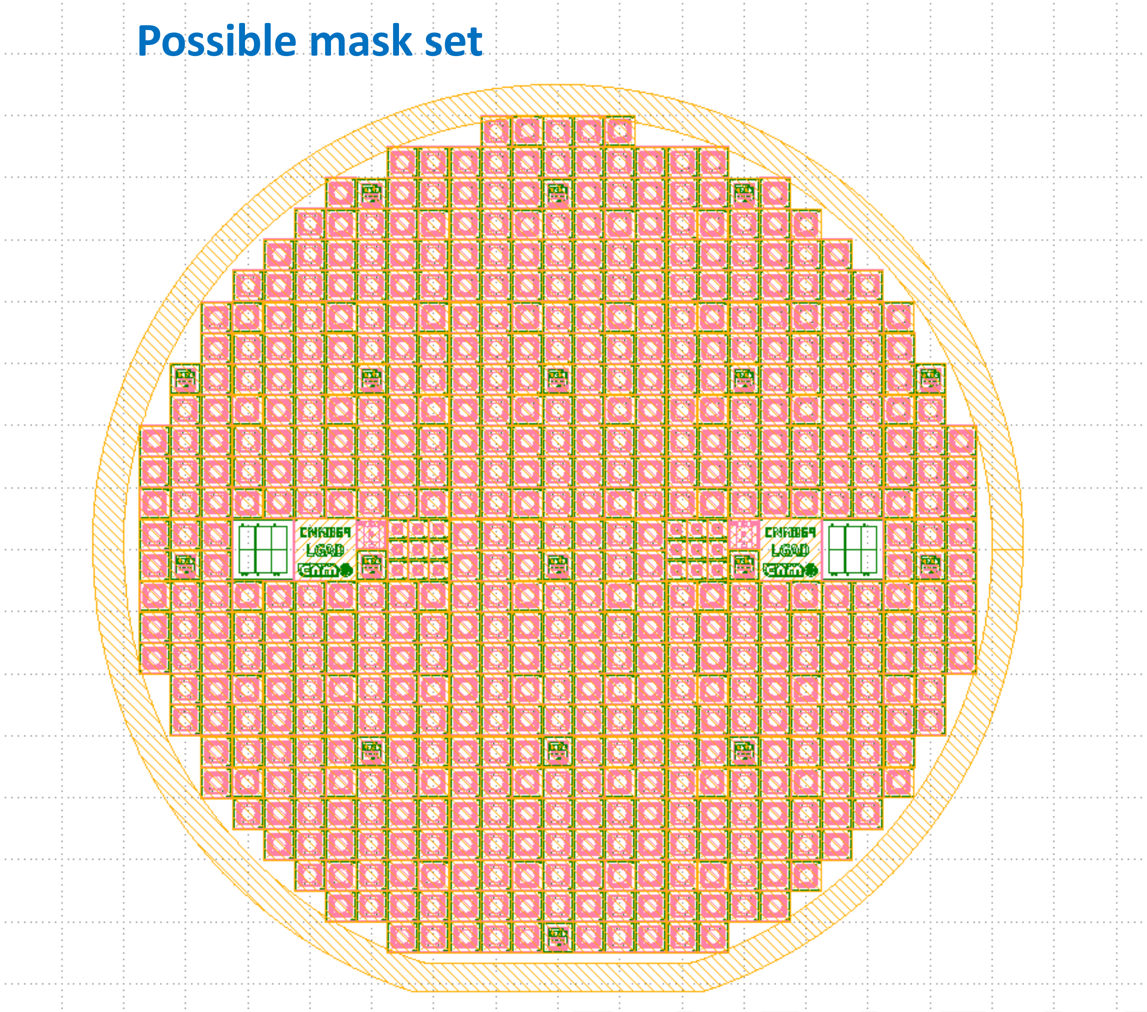
Figure 2: Isochronal annealing of boron. The fraction of activated boron, p/ϕ, is plotted against the annealing temperature, T_A, for different implant doses, ϕ. The annealing time is 30 minutes[doi:10.1080/00337577108232255].

Next steps

- **Once the PAB point is found we plan to start a run with full LGADs (pad)**
  - Will leave the boron activation for the last thermal process in the run
  - Will first evaluate the impact of metallization and passivation process on the total thermal budget
  - Will still keep a split for the boron activation step (variation from target on some wafers)

- **Run details (still TBD):**
  - Only pad structures (including some PiNs)
  - Deep boron implant, looking for better gain stability
  - Will use already existing mask set (still to select the optimal one)

Possible mask set



PAB Process

There are two potential approaches to incorporating not-active Boron into the PGAIN layer.

OPTION 1

Implant higher PGAIN dose
(es. ×2 Boron Dose)

↓

Partial Activation at low temperature (es. 50% activation)

Cons: difficult to exactly tune the activation time/temperature (dose dependent)

Pro: minimum PGAIN diffusion

OPTION 2

Implant PGAIN dose

↓

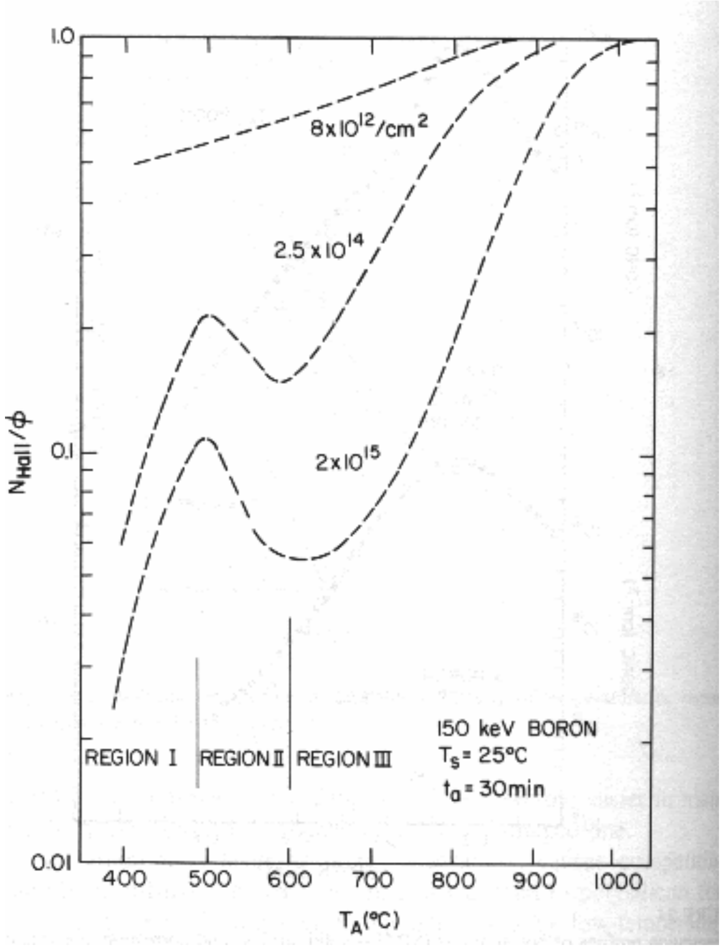
Standard Full Activation

↓

2nd Boron Ion Implantation
(not activated at all)

Pro: easier Gain tuning (provided that the parasitic thermal budget during the final part of the process does not activate the additional doping)

Cons: defects recovery?



Phase 1: Preliminary Investigation

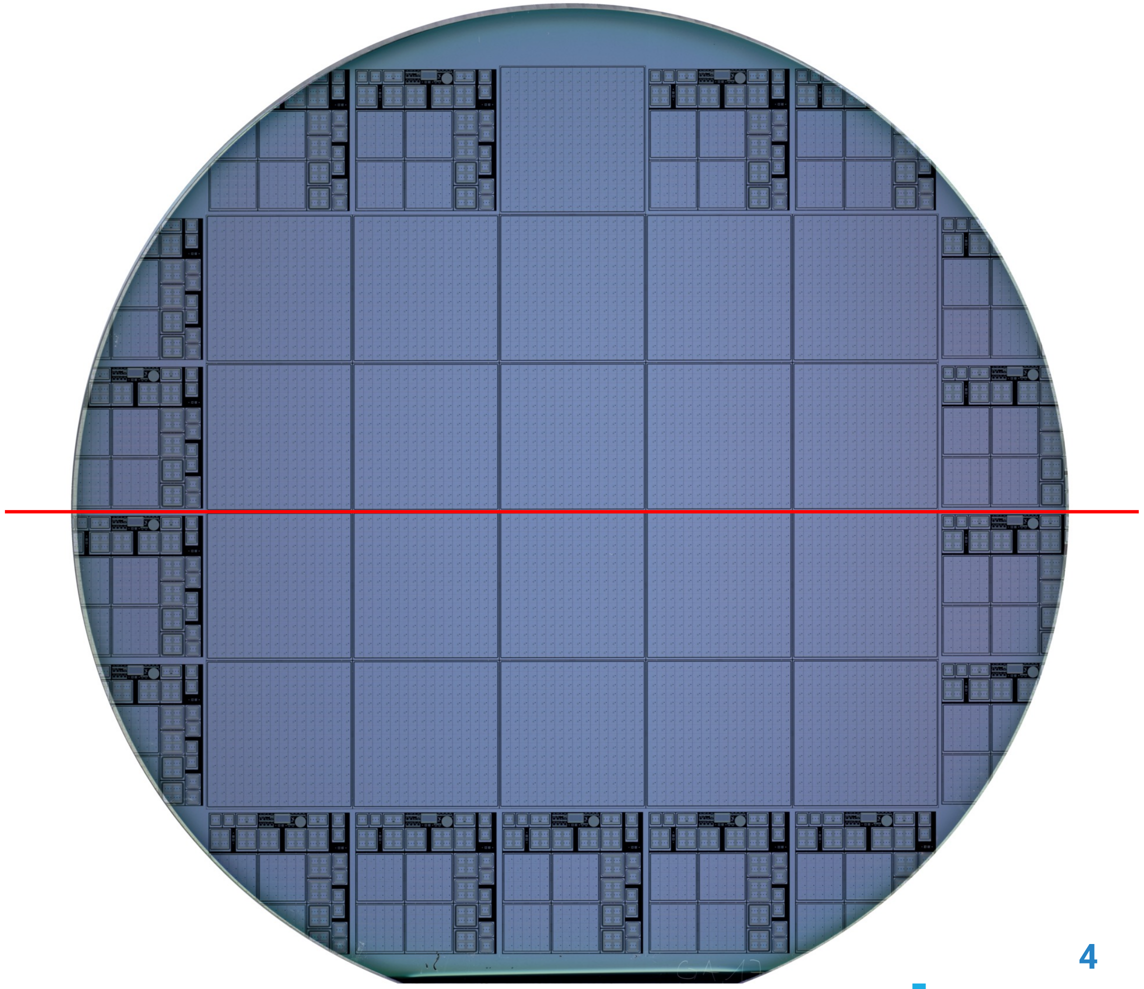
- We used two wafers from an ongoing CMS-LGADs production to investigate the first option 1 process
- The two wafers got a higher PGAIN dose (×2 and ×1.6), then were divided into two halves and annealed at two different temperatures

Half Wafer	Dose PGAIN*	ANNEALING TEMPERATURE
W17 TOP	**1.6**	**T1**
W18 TOP	**2**	**T1**
W17 BOTTOM	**1.6**	**T2**
W18 BOTTOM	**2**	**T2**

T2 > T1

*In units of FBK PGAIN dose

WAFER 17, 18 UFSD_K1

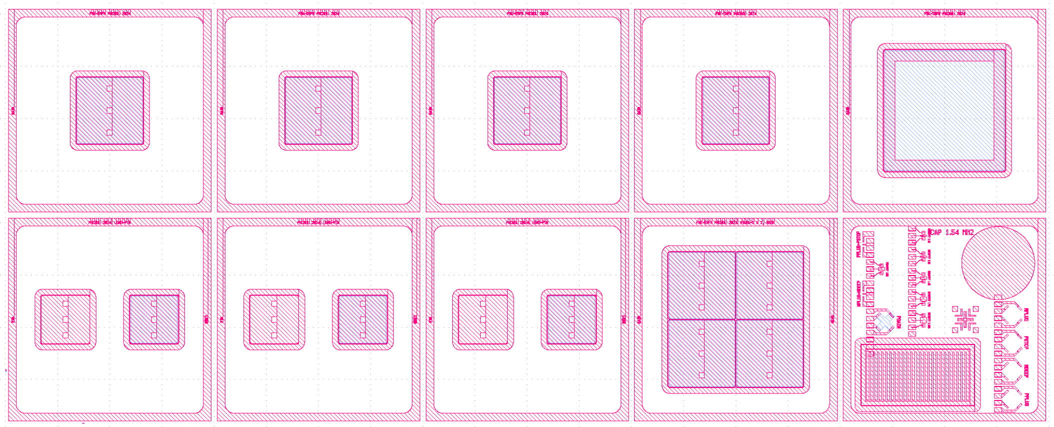


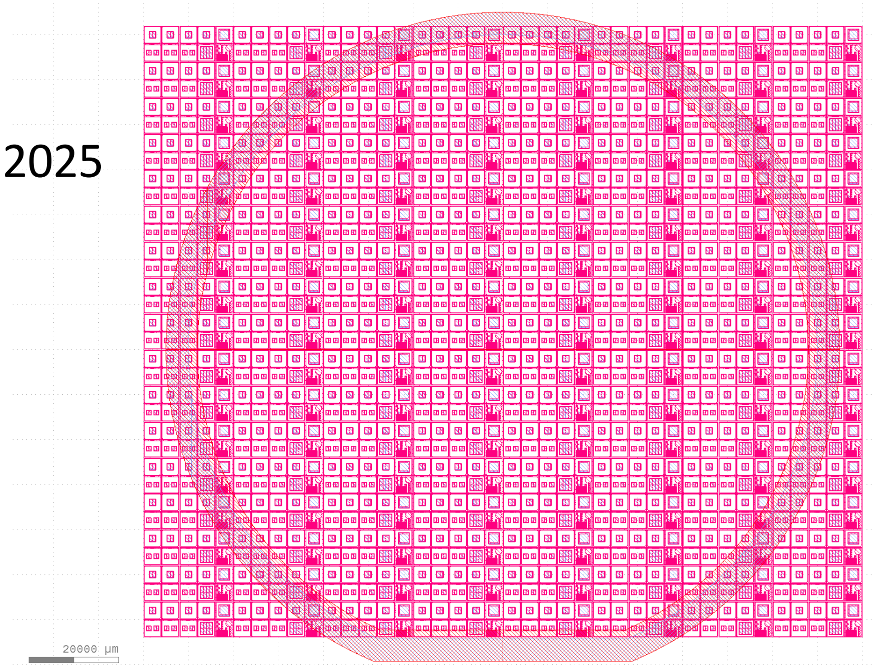
Phase 2: Dedicated production

- FBK will produce dedicated wafers for PAB in a new batch (6-8 wafers)
- Process option 1 or option 2 will be used (also depending on the outcome from phase 1)

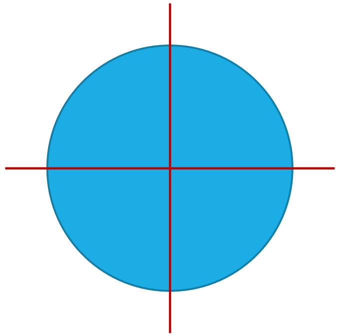
Timeline

- Preliminary tests (phase 1) ⟶ ongoing
- Electrical characterization of Phase 1 test ⟶ beginning of 2025
- New production for PAB ⟶ start in March 2025 – completed by June 2025





Summary & Outlook



For the wafer productions

▻ each wafer will be cut into 4 parts that will receive different annealing

⟶ **The selected masks ensure enough sensors for each participant in the project**

⟶ **The high number of participants (!) requires a fair sharing of sensors and information between the project participants**

⟶ **Outcomes from the short loop runs will be available soon**

⟶ **Start of PAB sensor productions expected by mid 2025**

Extras

Sensor Irradiation

After the characterisation of sensors, two irradiation campaigns will be organised

JSI:
Proposal: sensors will be irradiated to fluences comprised between 4E14 to 5E15 n_{eq}/cm^2
Project: **8 – 15 – 25 – 35E14** $\mathbf{n_{eq}/cm^2}$?

Helsinki:
The 10 MeV proton accelerator at the Helsinki Institute of Physics will be exploited to investigate the effects of the irradiation with low-energy charged particles on the PAB sensors
What Φ ? **2 – 4 – 8E14** $\mathbf{n_{eq}/cm^2}$?

→ Given the number of institutes participating in sensor testing, a dedicated plan for sensor collection and preparation of the common irradiation campaign will be necessary

Sensor Characterisation & Testing

- C-V measurements will be performed on all sensors before and after irradiation to extract the doping profile of the activated boron implant and map its evolution with the collected fluence
- TCT and beta measurements will map the change of the transient behaviour with irradiation
- I-V, TSC, and DLTS measurements will be performed to map the presence of defect states and their rise after neutron and proton irradiation

Project Schedule & Deliverables

Tentative project schedule

- ▻ Short loop at CNM – M6
- ▻ Release of the 2 explorative wafers from FBK – M6
- ▻ Batch productions with boron and boron + carbon gain implant from CNM and FBK – M12
- ▻ Sensor testing before irradiation – M15
- ▻ Sensor irradiation – M18
- ▻ Sensor testing after irradiation – M24

Project deliverables

⟶ Parametrisation of the boron activation as a function of the temperature for LGADs – M12

⟶ Best production parameters to design Partial Activated Boron LGAD – M24