TCT for the characterization of silicon interfaces obtained by CMOS compatible wafer bonding

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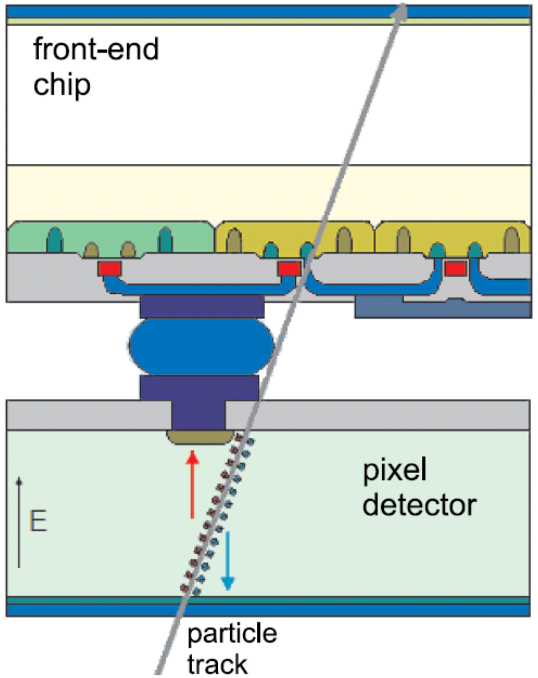
[1]https://ep-dep-dt.web.cern.ch/
[2]http://www.leti-cea.fr/cea-tech/leti/Pages/innovation-industrielle/innover-avec-le-Leti/LETI-3S.aspx
[3]https://edlab.epfl.ch/

Outline

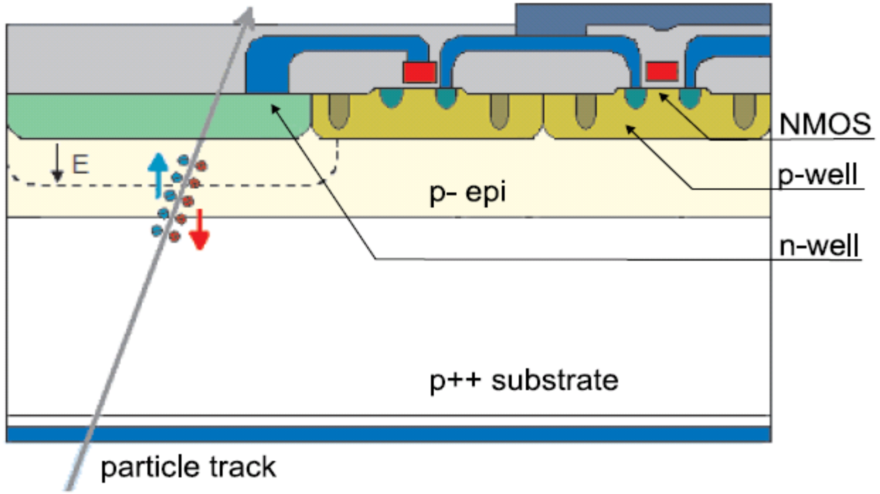
- CMOS compatible wafer bonding for the fabrication of silicon detectors
- Electrical characterization of Si-Si bonded interfaces
- Proof of principle of electrical injection TCT

Silicon pixel detectors

Hybrid



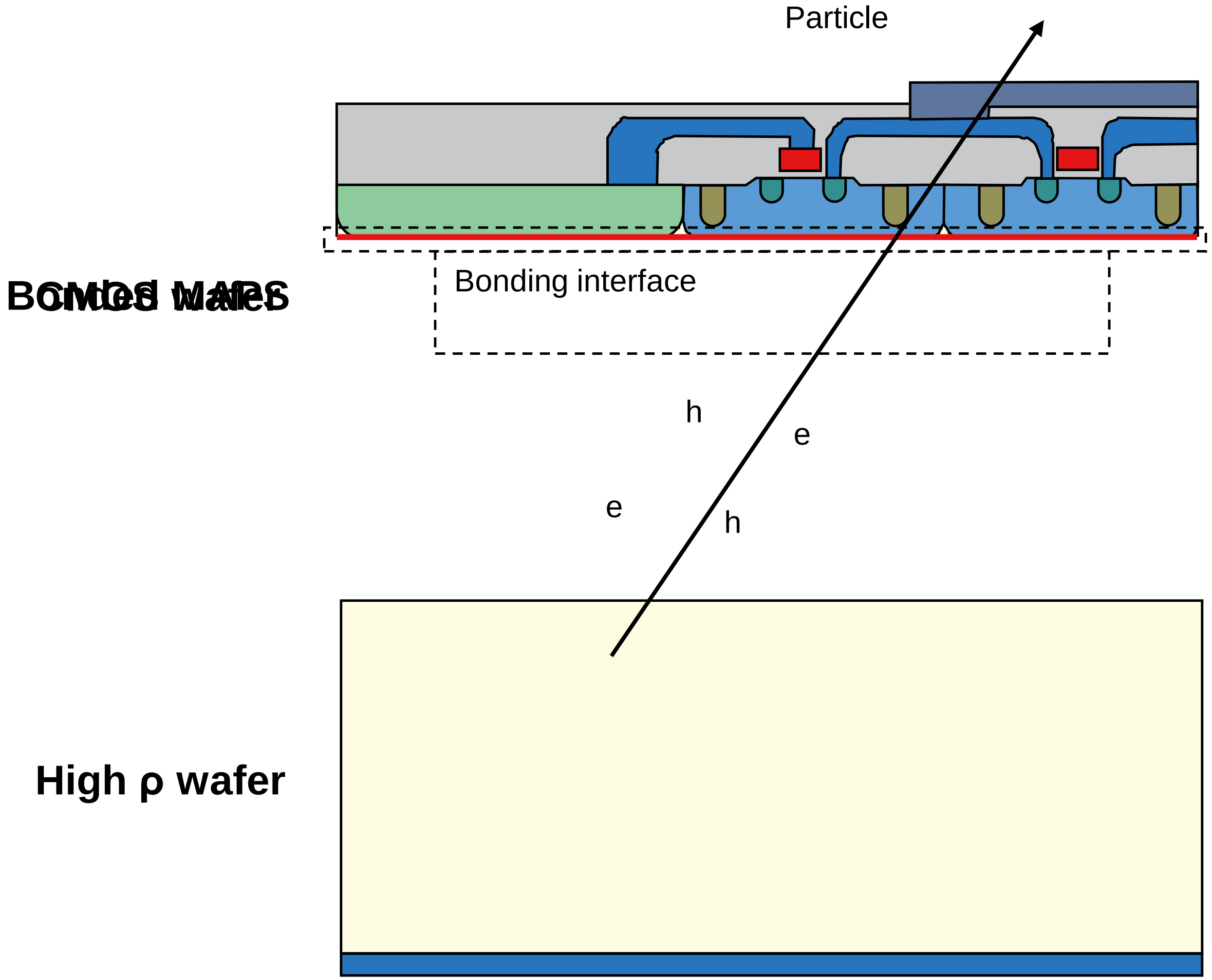
Monolithic



L. Rossi et al., Pixel Detectors: From Fundamentals to Applications, *Springer*, 2006.
P. Riedler, Monolithic silicon pixel sensors and technology challenges of the ALICE ITS, 2015,
https://indico.cern.ch/event/352490/attachments/1155083/1659960/DT_training_seminar15092015.pdf

Bonding of monolithic detectors

- Motivation: possibility of choice of different bulks type
  - High resistivity silicon for sensing
  - Low resistivity silicon for CMOS circuit
- CMOS compatible wafer bonding for monolithic pixel detectors:
  - Thinning of CMOS wafers
  - Bonding with sensing bulk
    - Low temperature (<400°C)
    - Silicon bulk fracture strength reached
    - Oxide-free interface
- Conduction properties of the bonding interface to be characterized



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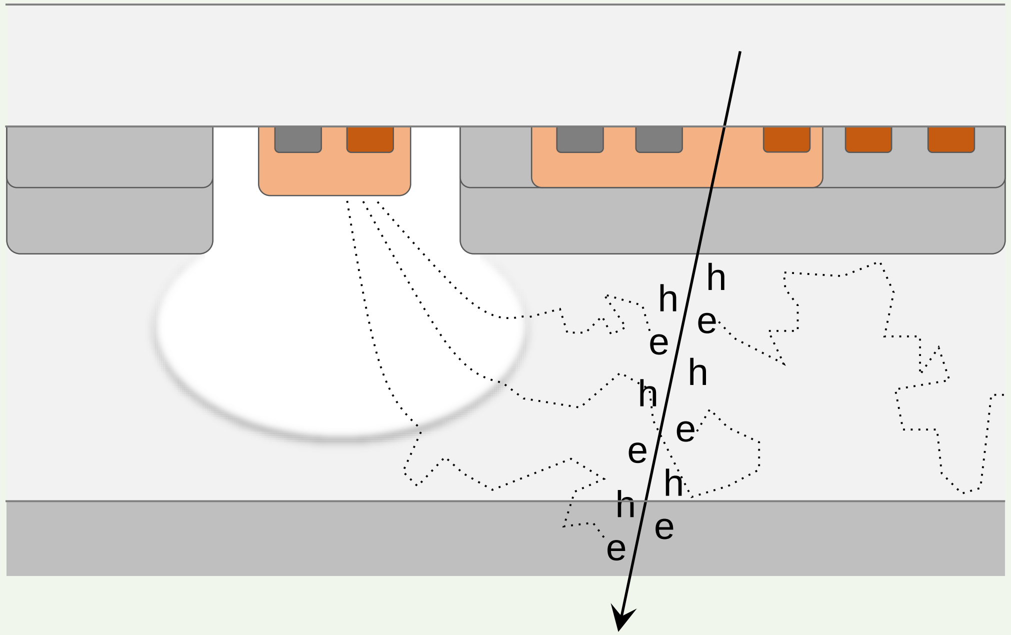
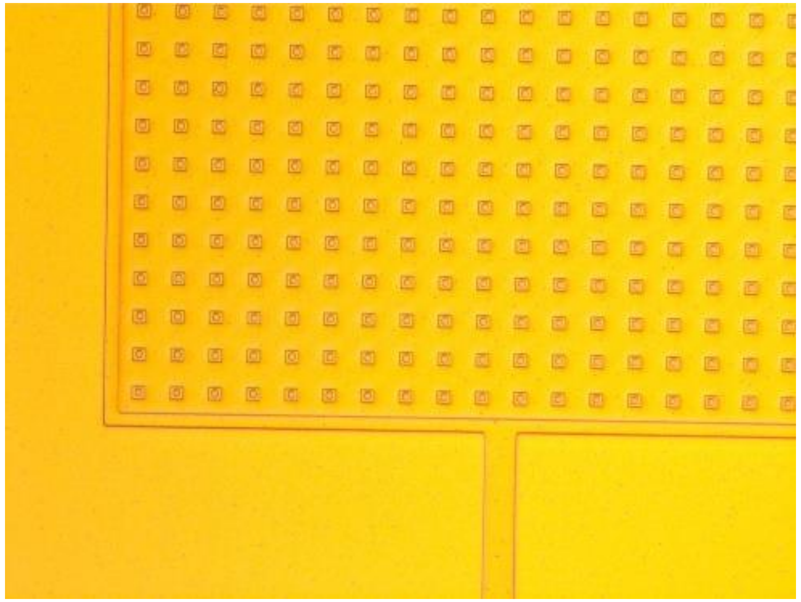
Two investigation approaches

INVESTIGATOR from ALICE ITS



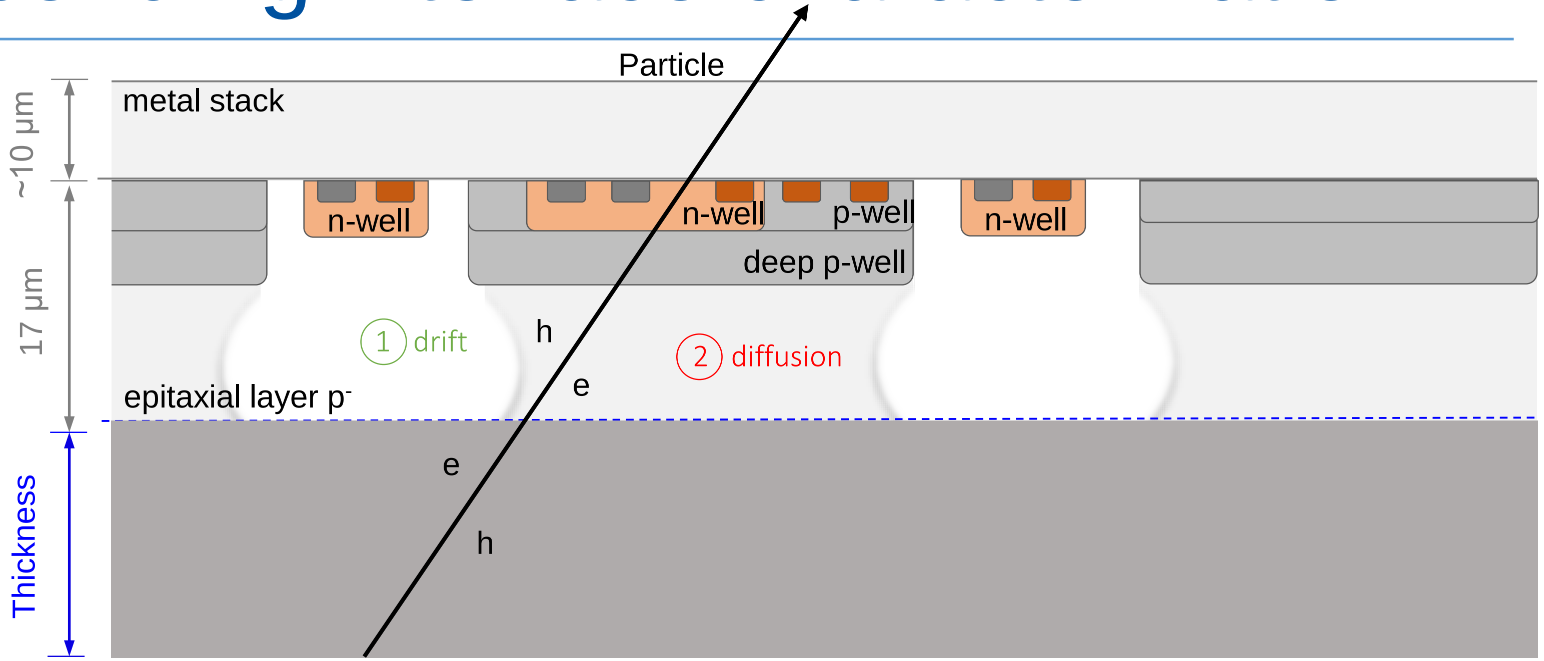
TCT on Schottky diodes



INVESTIGATOR for bonding interface characterization

Standard INVESTIGATOR from ALICE ITS:
- Different layouts tested
- Epitaxial layer (> 1 kΩ cm) on low resistivity silicon wafer

Bonded INVESTIGATOR (fabricated by G-ray):
- Thinning of back side of ITS wafer
- Surface preparation
- Bonding to different types of silicon wafers



Test list	
Bottom wafer	**Thickness**
High resistivity silicon bulk > 5 kΩ cm	700um
	90um
	55um
Epitaxial silicon Epi > 1 kΩ cm	Epi 20um, Bulk 700um

1. Drift: charges in the depletion region are collected by the corresponding n-well
2. Diffusion: charges diffuse in silicon. If they reach a depletion they are collected.
   - Charges generated from one particle can be collected by different n-wells (charge sharing)
   - Diffusing charges are reflected by low resistivity silicon bulk

Measurements on bonded INVESTIGATOR chips – Fe55

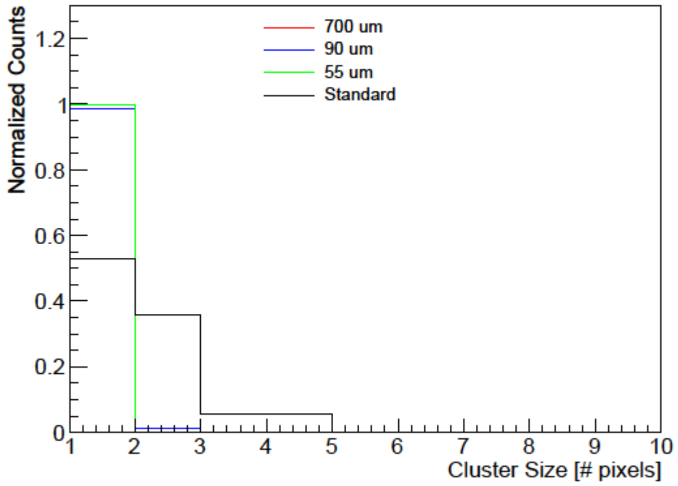
Cluster multiplicity (number of pixels collecting charges per event) < 2

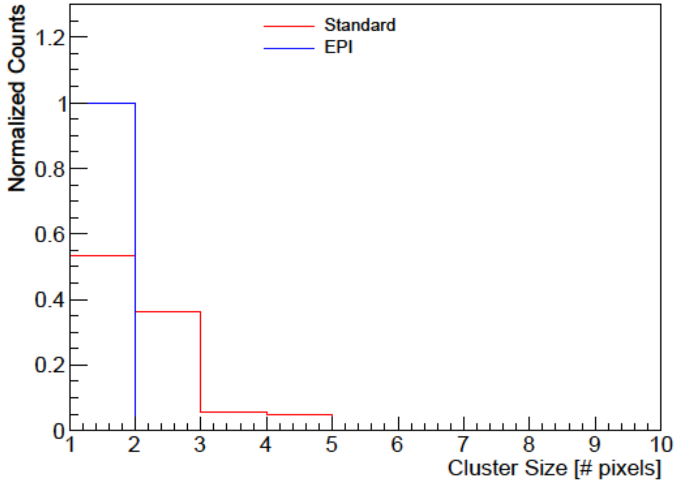
Absence of charge sharing

Charges pass through the interface and diffuse in the bulk

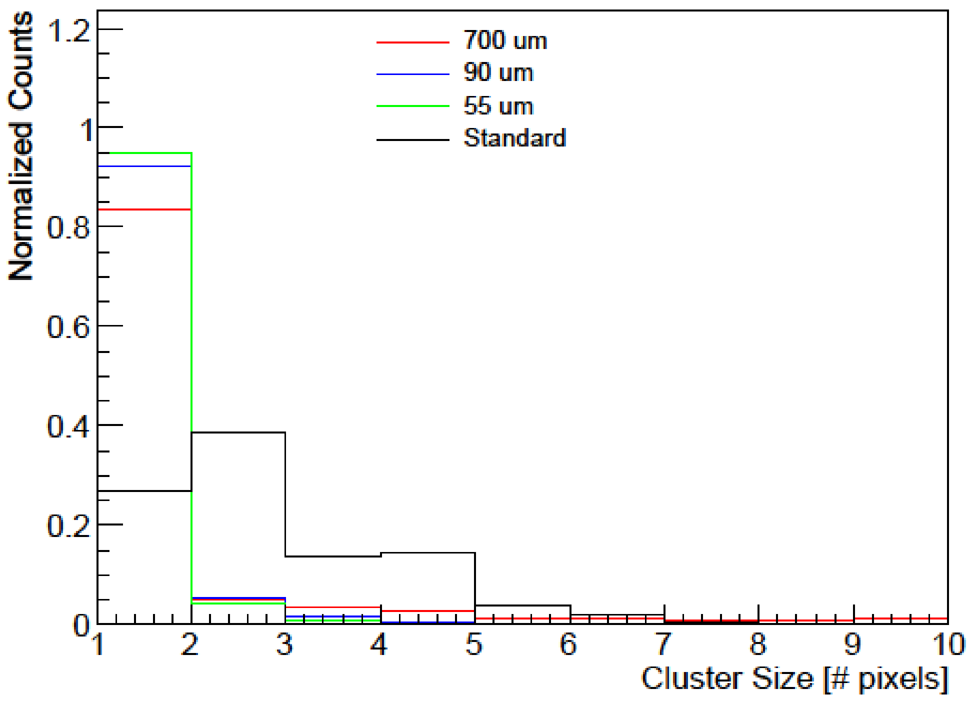
Charges are absorbed by the interface

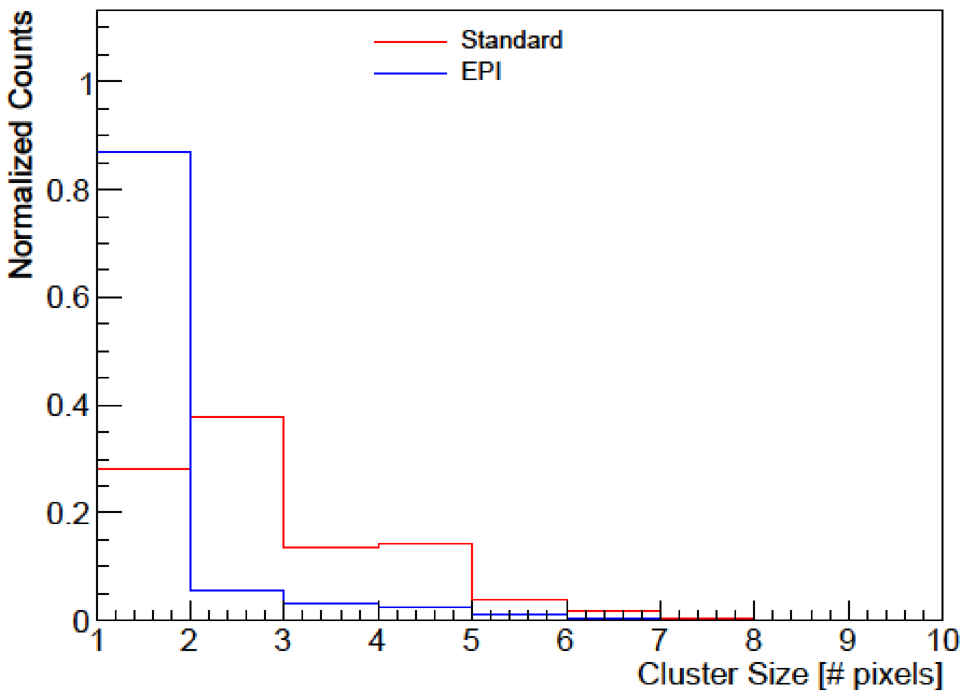
There should be charge sharing for epitaxial silicon substrates





Measurements on bonded INVESTIGATOR chips – Sr90

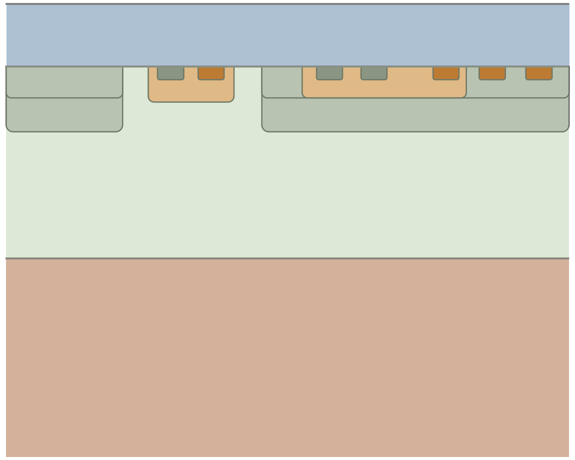




- Weak charge sharing observed
- Consistent with the hypothesis of not conduction through bonding interface

SEM analysis of bonded INVESTIGATOR

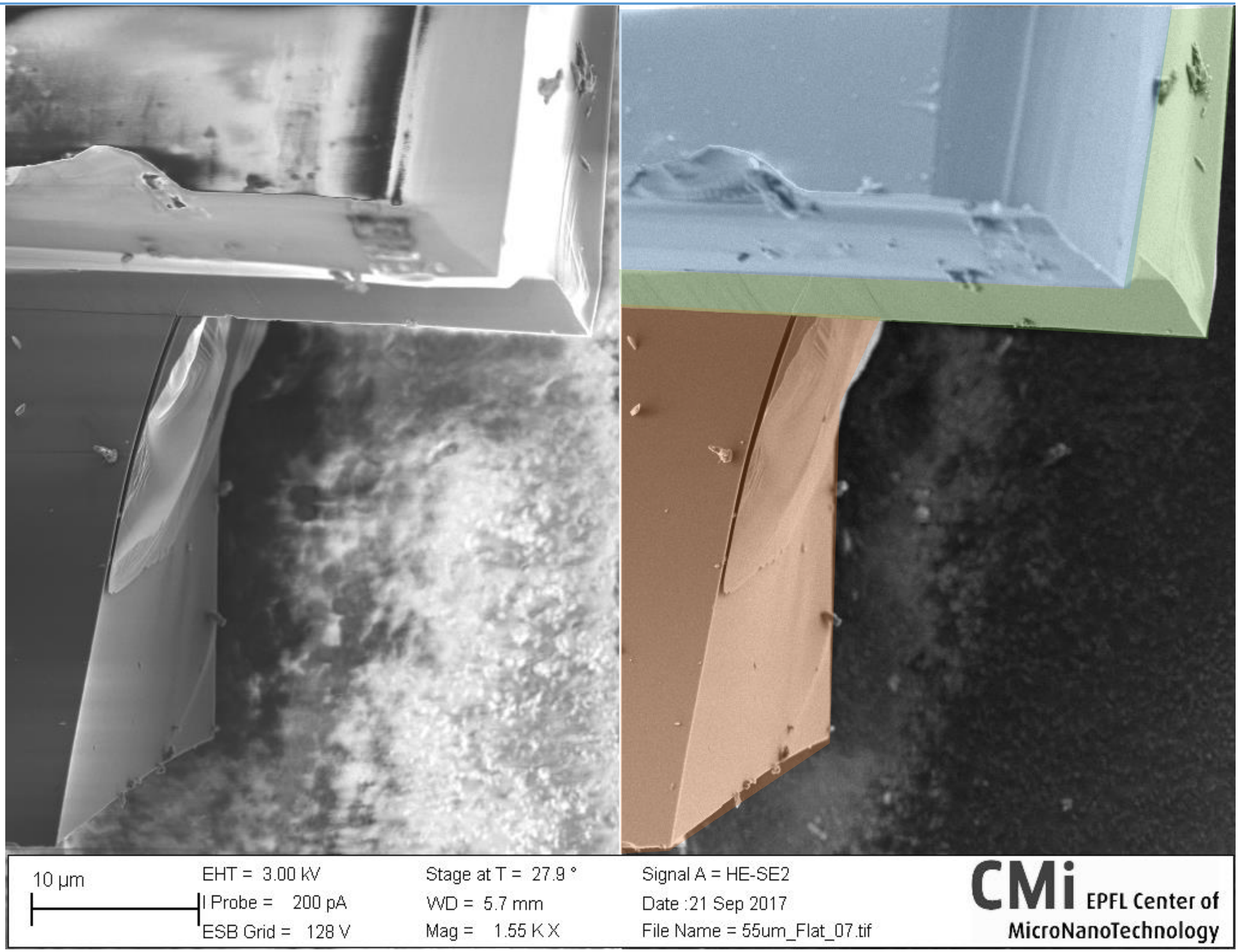
INVESTIGATOR cross section



Metal layers

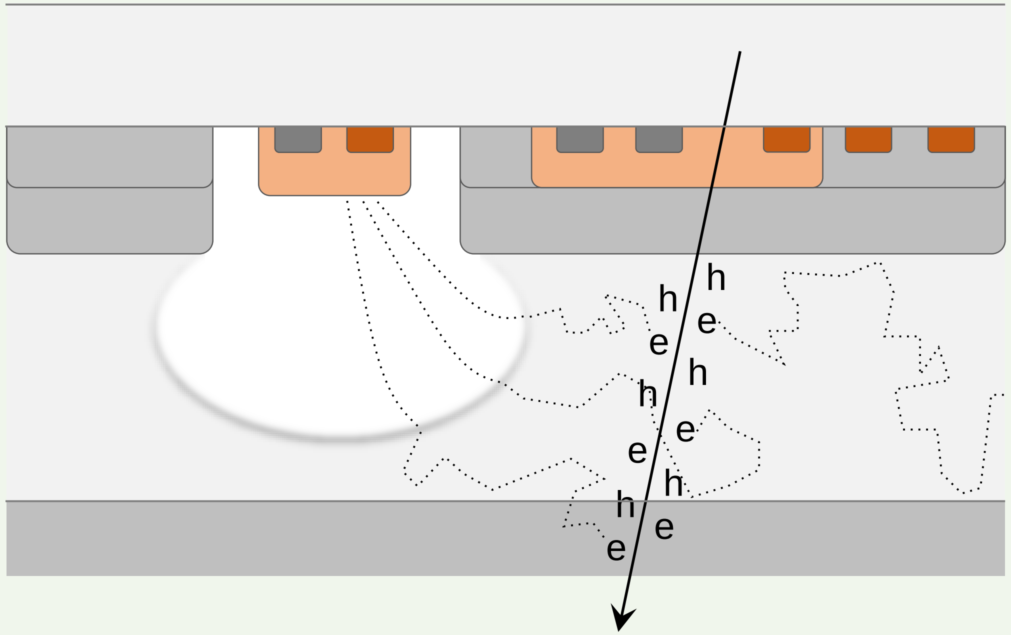
Epitaxial silicon

High ρ silicon

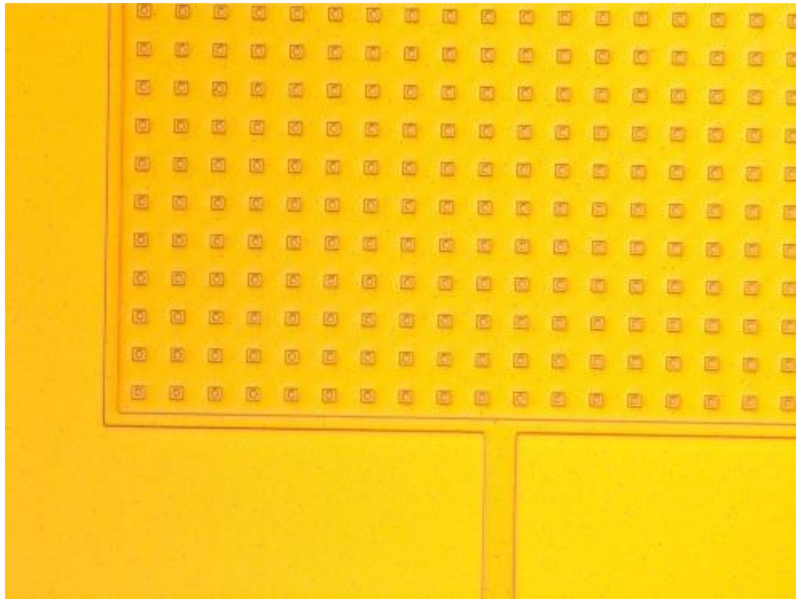


Two investigation approaches

INVESTIGATOR from ALICE ITS



TCT on Schottky diodes

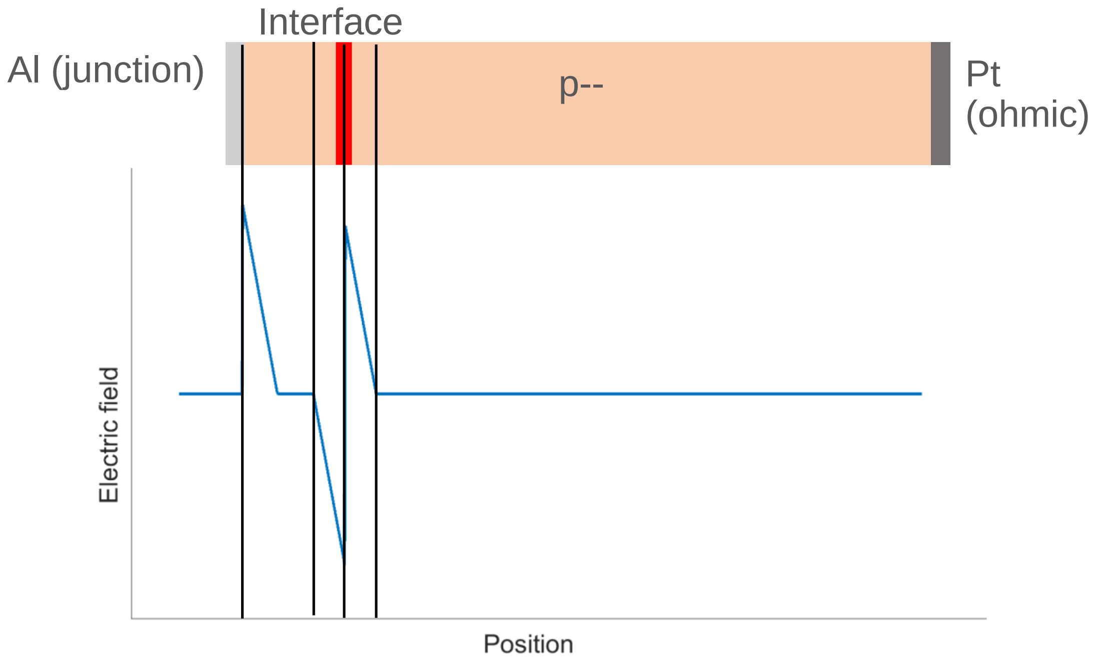


TCT for bonding interface characterization

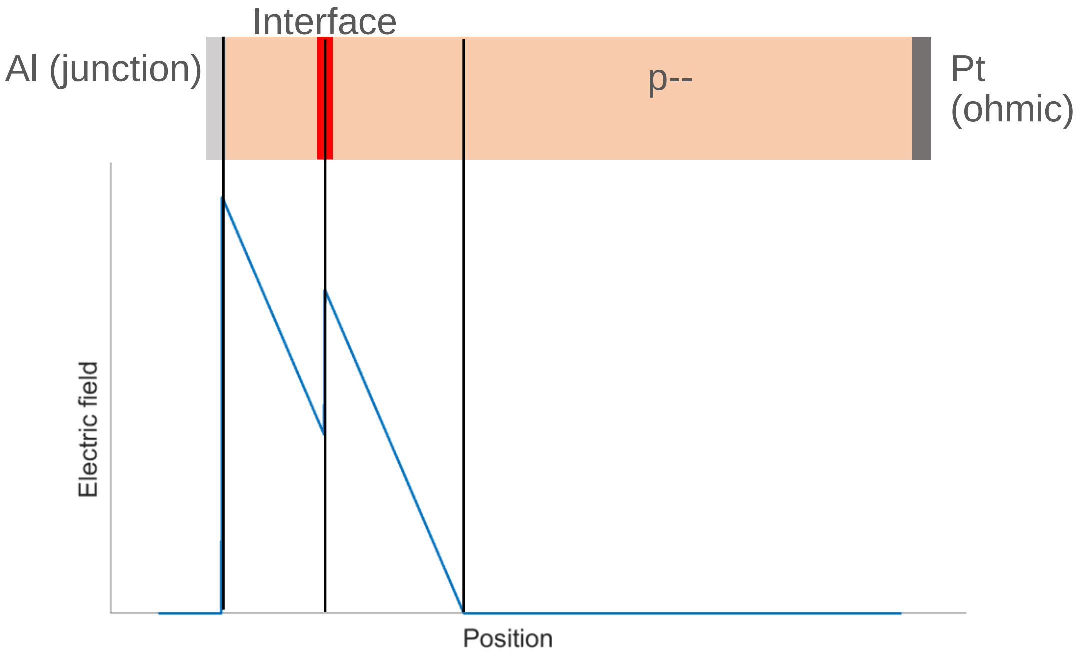
Amorphous silicon at the bonding interface can be modeled as a layer with a trap density 1e16 cm^{-3}

Analytical modeling of TCT transient current for bonding interfaces, 2 cases:

Junction depletion region does not reach the interface



Junction depletion region reaches the interface

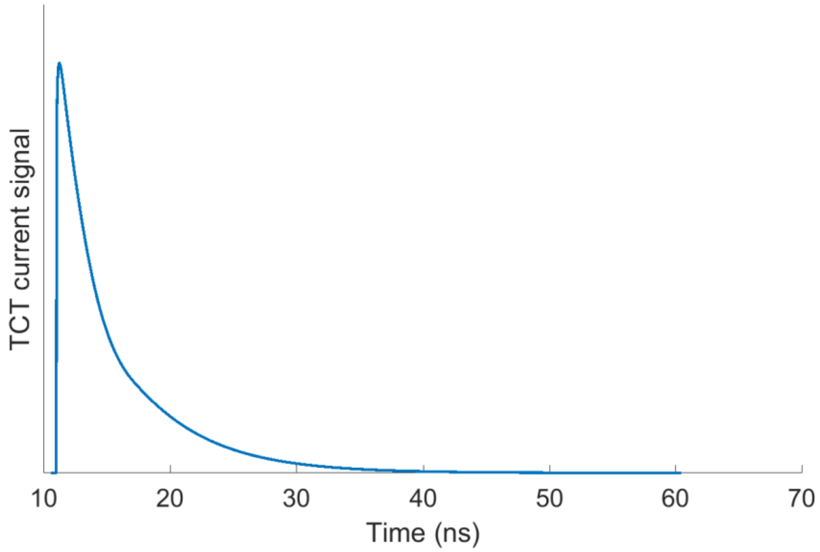


J. Bronuzzi et al., "*Principle and modelling of transient current technique for interface traps characterization in monolithic pixel detectors obtained by CMOS-compatible wafer bonding*", *JINST,* 11 P08016, 2016.

TCT for bonding interface characterization

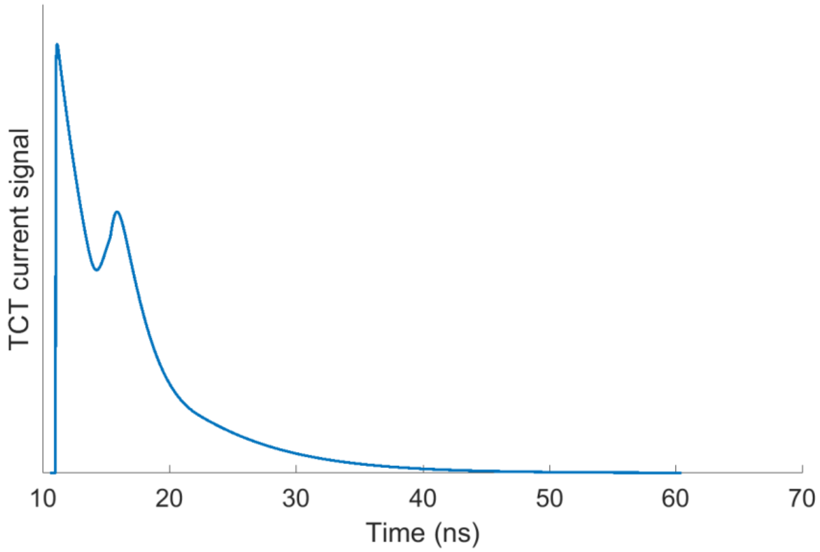
Traps not detected

- **Low voltage**: depletion region does not reach traps layer
- **Presence of both donors and acceptors in same quantity**: ionized traps will result is neutral charge
- **Presence of acceptor**: ionized acceptors generate negative charge that do not give double peak electric field



Traps detected

- **High voltage**: depletion region reaches traps layer
- **Presence of donors**: ionized donors generate positive charge that gives double peak electric field



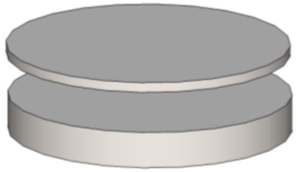
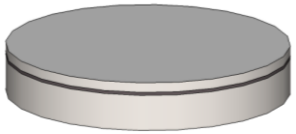
Test structures fabrication

CMi EPFL Center of MicroNanoTechnology

CMOS compatible bonding of silicon wafers at CEA-LETI:

- Silicon wafers: 8 inches, magnetic Czochralski P-type, ρ > 5000 ohm.cm
- Thinning (tolerance 1 µm), to have interface close to surface, and bonding (pressure 30 kN)
- Downsizing from 8 inches to 4 inches through laser cut (Sil'Tronix)
- Bonding parameters:
  - Top wafer thickness: 20 µm, 50 µm
  - Surface preparation: hydrophobic, hydrophilic
  - Annealing temperature: 400 °C, T amb
- Fabrication of Schottky diodes on top of wafers at the Center of Micronanotechnology (CMi) at EPFL, to be studied with TCT

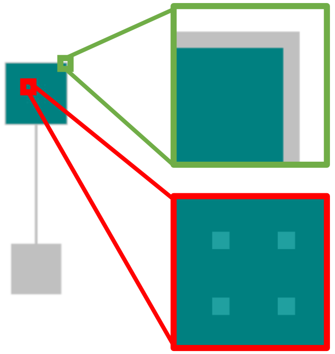
CMi: https://cmi.epfl.ch/

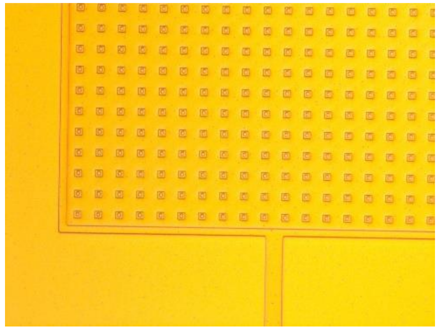
Start wafers	
Thinning top wafer	
Bonding	
Downsizing	
Schottky diodes fabrication	

Validation of TCT on Schottky diodes

- Tests performed on structures fabricated at CMi
- 4 inches wafers
- Resistivity > 2000 ohm.cm
- Float zone P-type
- Al for schottky contacts
- Pt for ohmic contacts

Diode

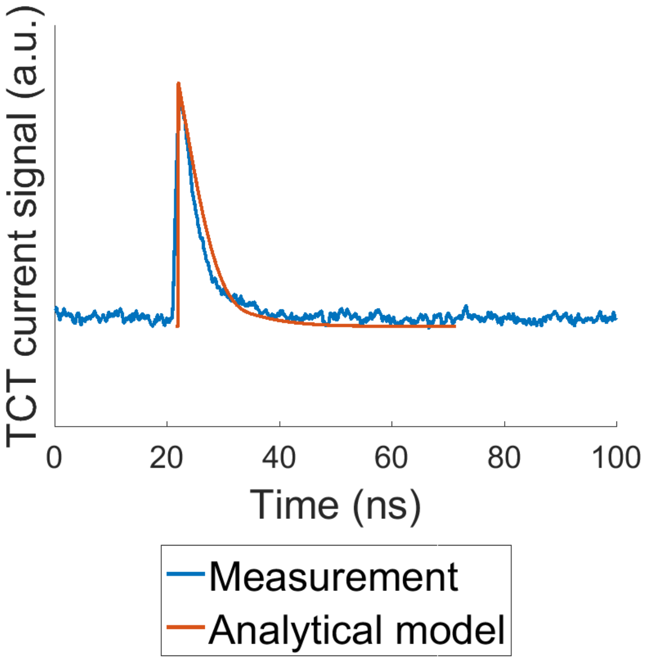




Next steps:

- Schottky diodes fabrication on bonded wafers
- TCT measurements on Schottky diodes on bonded wafers

TCT signal (at 40 V)



CMi: https://cmi.epfl.ch/

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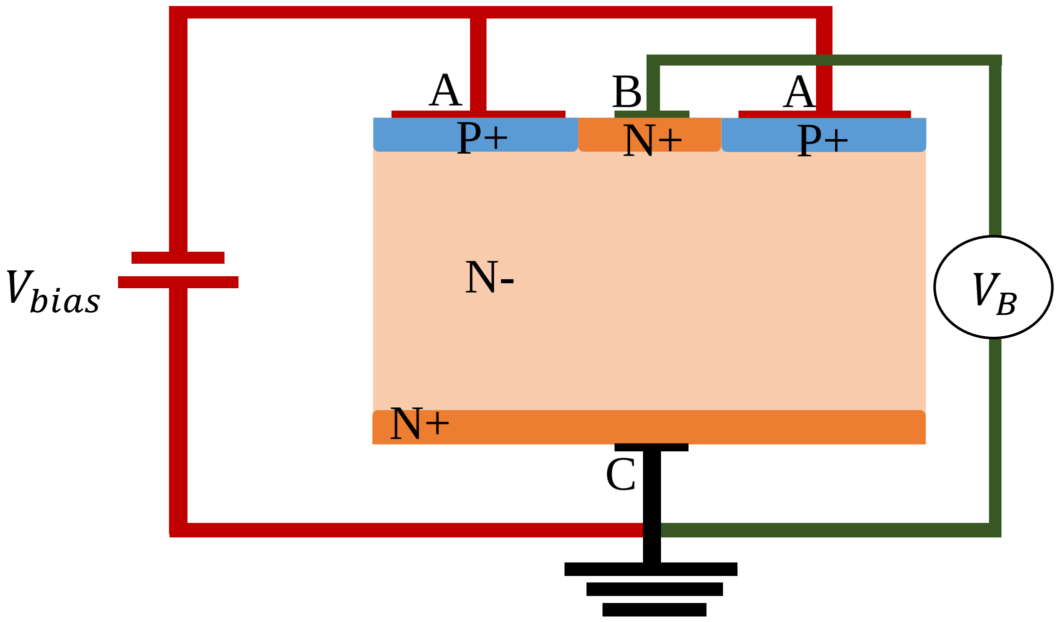
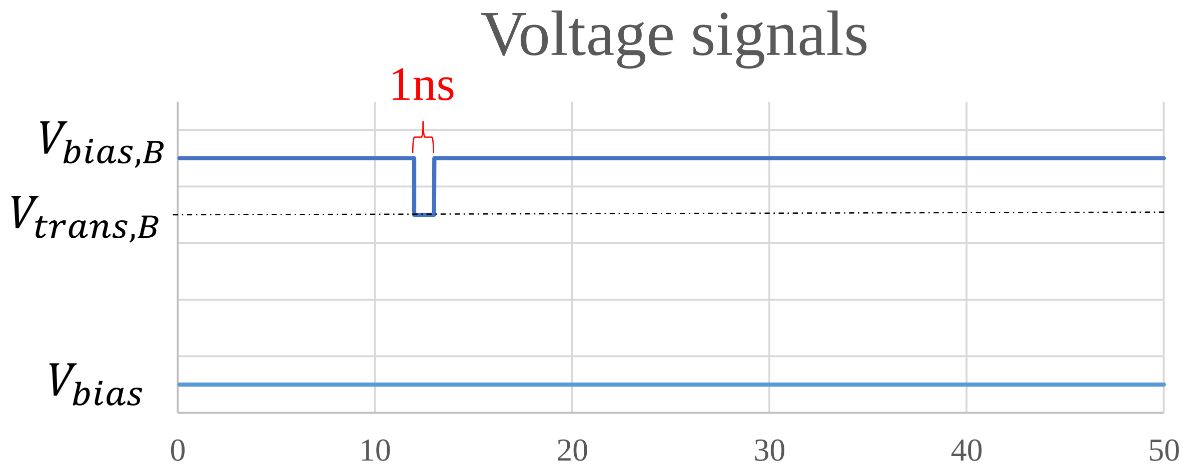
Electrical injection TCT

- Instead of Schottky diodes, integrate TCT charge injection in silicon
- PiN Diode doping profile modified
- Nanosecond voltage pulse applied on the N-type well

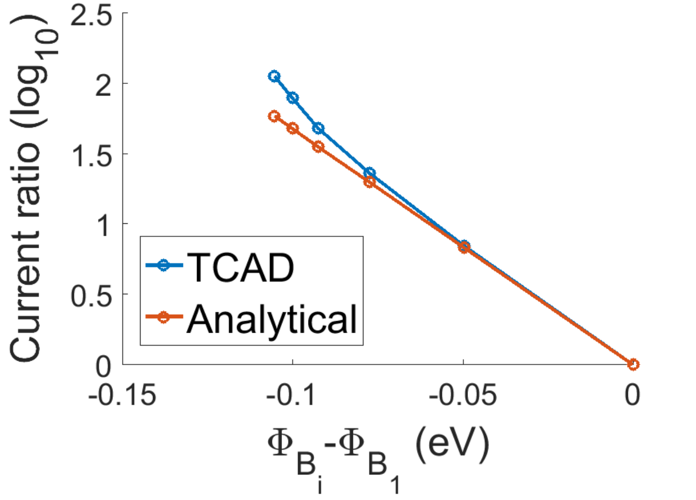




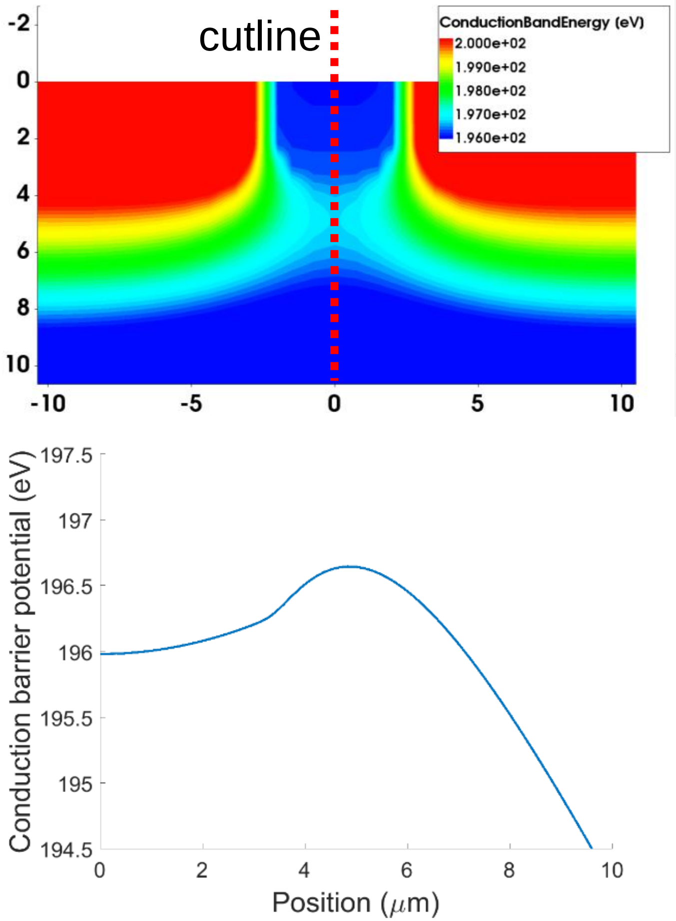
Physical principle

Thermionic emission

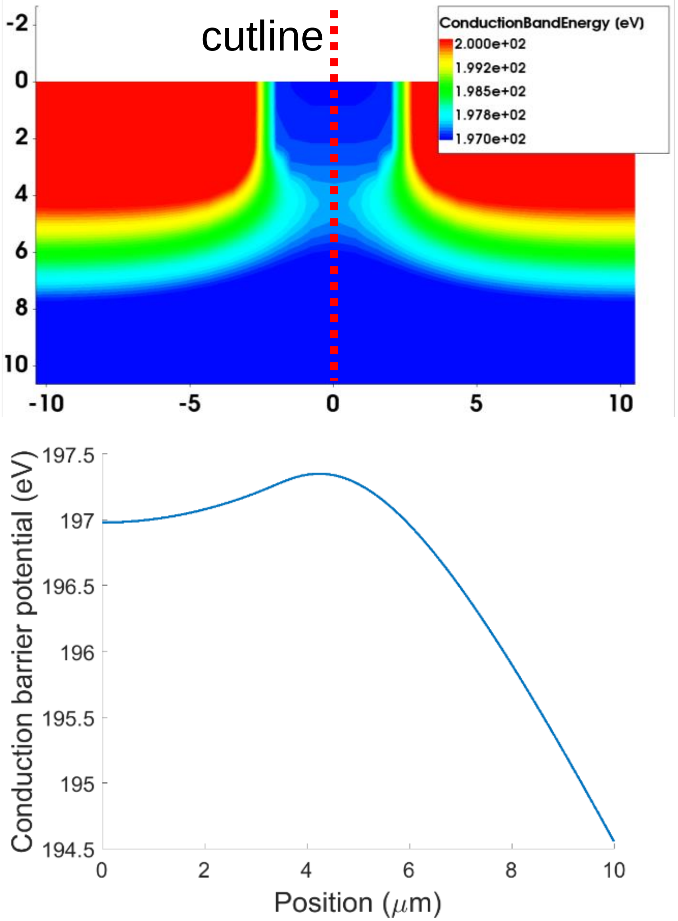
$$J_i/J_1 = e^{\frac{\phi_{B_1}-\phi_{B_i}}{kT}}$$



Steady state



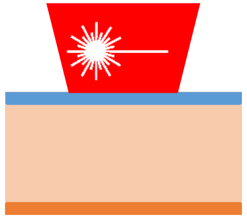
Injection

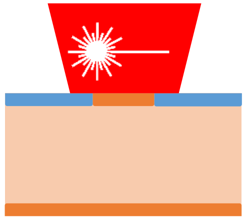


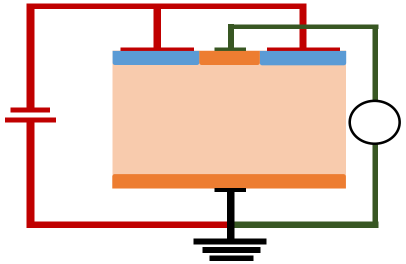
Light and electrical injection

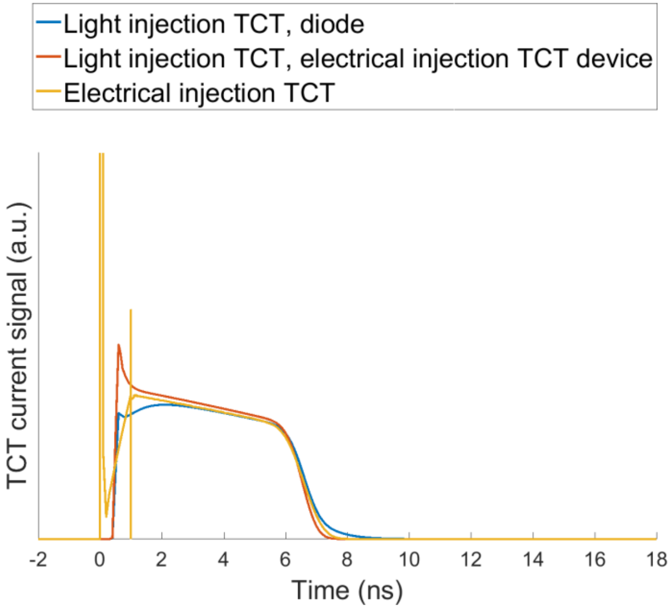
3 Studies

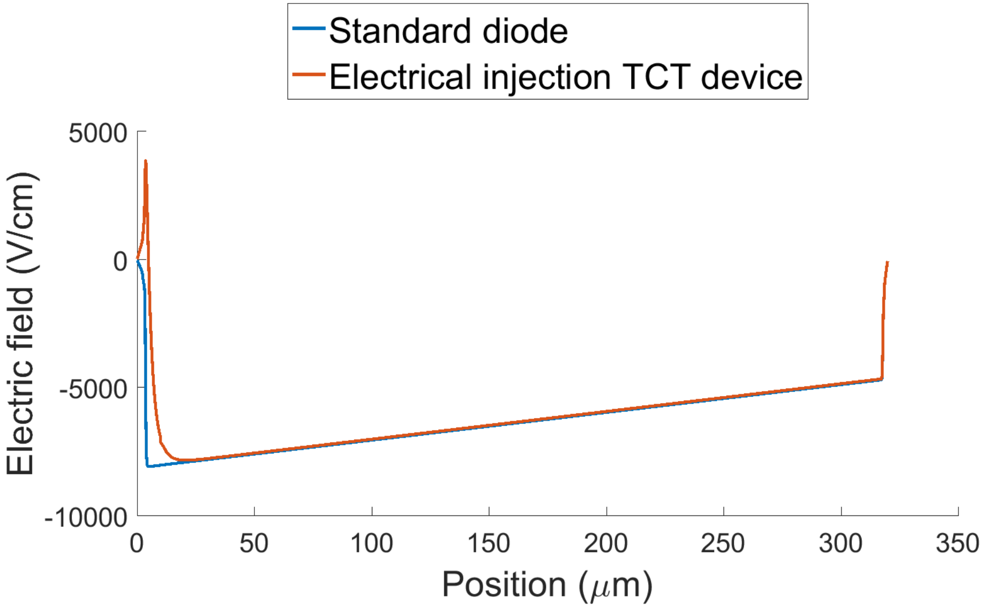
Optical injection on standard diode	Optical injection on Electrical injection TCT (el-TCT) device	Electrical injection





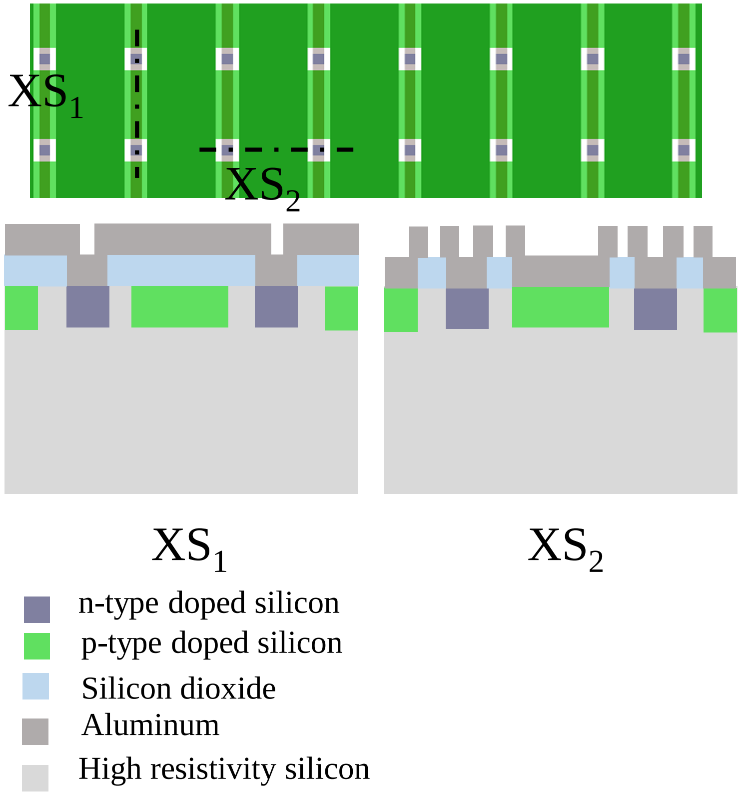


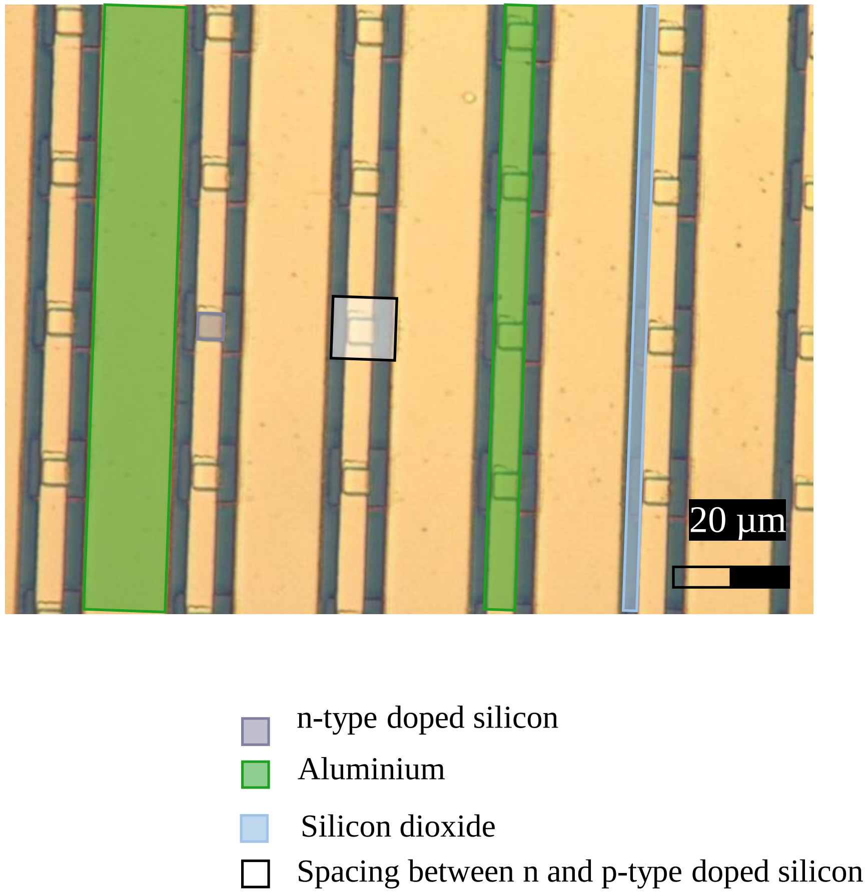




Fabrication and measurements setup

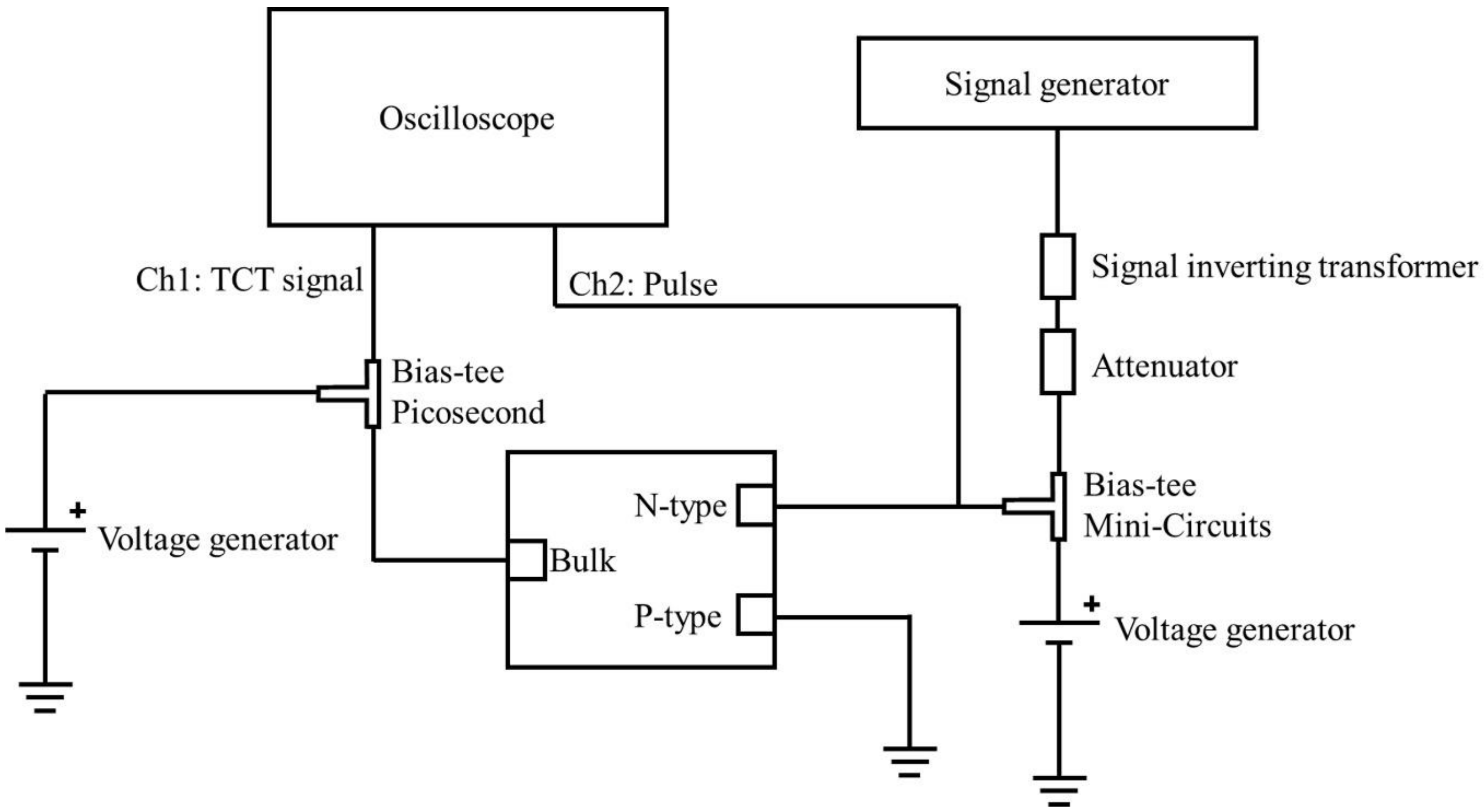
Device fabricated at CMi





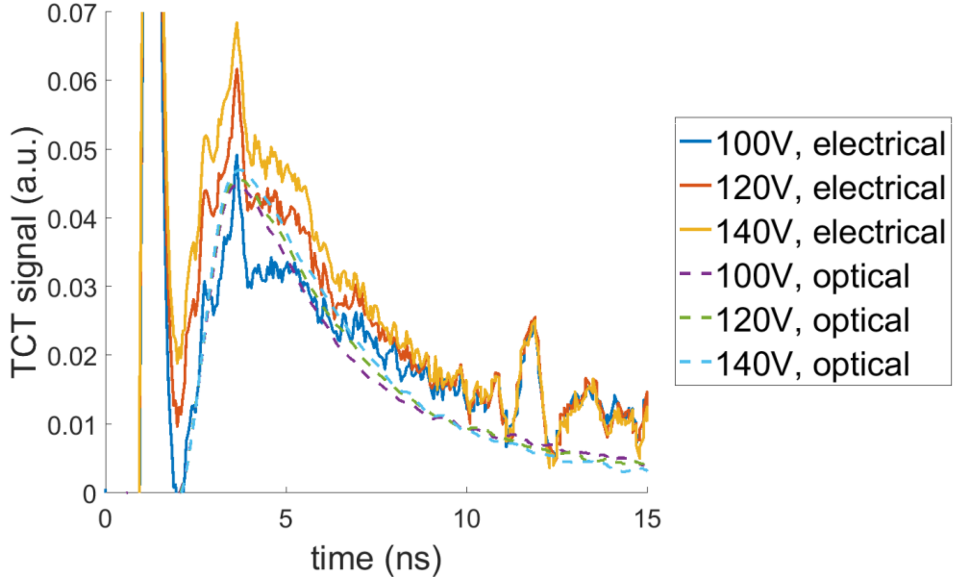
Setup components

- Signal generator: Picosecond Pulse Labs 10,050A
- Bias-tees:
  - Picosecond Pulse Labs 5531
  - Mini-Circuits ZFBT-6GW
- Voltage generators:
  - Keithley 2410
  - Agilent E3631A
- Oscilloscope: infiniium MSO9404A



Proof of principle of el-TCT

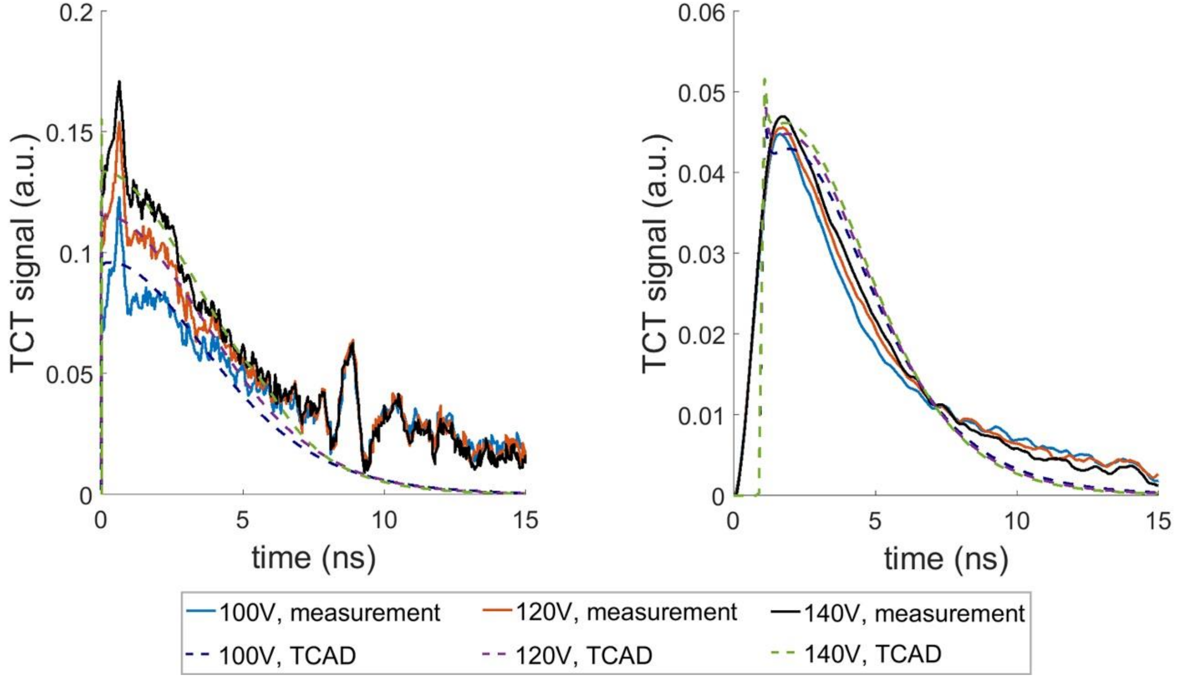
Measurements: comparison electrical and optical TCT



Comparison TCAD simulations and measurements

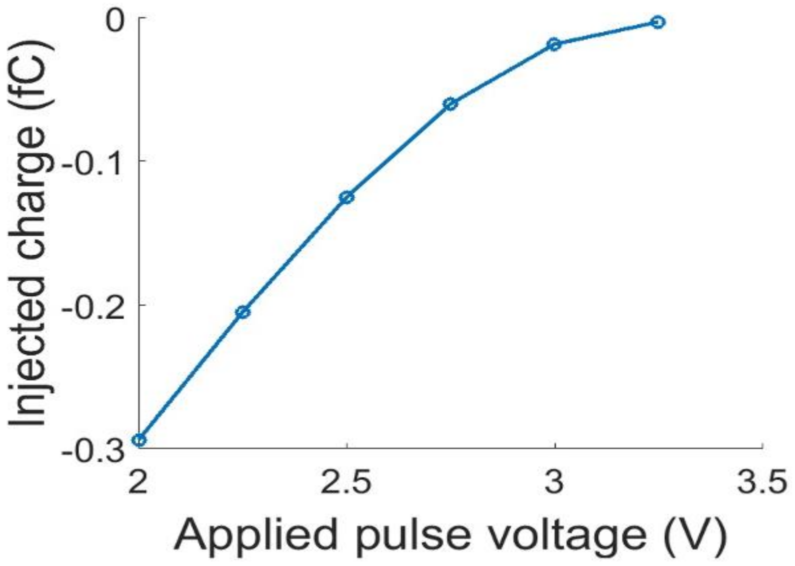
Electrical TCT

Optical TCT

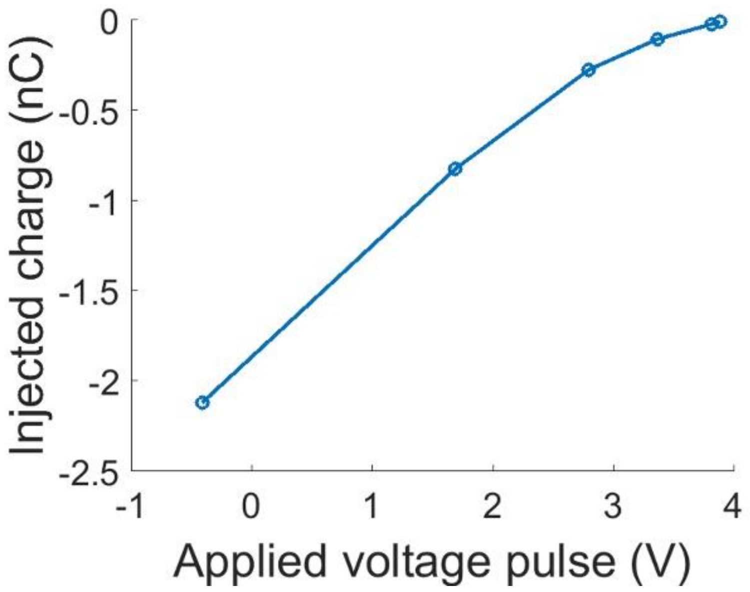


Proof of principle of electrical TCT

TCAD simulations of injected charge



Measurements of injected charge



- Charge calculated as the integral of the transient current in time
- Measured charge has a behavior similar to simulated charge
- Measured charge follow the same physical principle of simulated charge, thermionic emission

Conclusions and outlook

Direct wafer bonding is being investigated for an "hybrid" approach to manufacture monolithic pixel detectors.

- A model for TCT across silicon bonded interfaces has been developed.
- INVESTIGATOR wafers have been thinned and bonded to different types of substrates to study the bonding interfaces.
- Shottky diodes will be fabricated on already bonded plain wafers to study the interfaces with TCT at the beginning of 2018.

A new type of charge injection has been studied for TCT.

- Principle of electrical injection TCT (el-TCT) has been proven.
- El-TCT will be evaluated for online measurements of radiation induced damage in silicon samples in IRRAD next year.

Thank you for the attention
Questions?

Fabrication of monolithic pixel detectors

Electronics driven

- Low resistivity silicon
- High performance electronics
- Low performance sensing (small depletion region)

Sensor driven

- High resistivity silicon
- Difficult electronics design
- High performance sensing (large depletion region)

L. Rossi et al., Pixel Detectors: From Fundamentals to Applications, *Springer*, 2006.