Hydrogenated amorphous silicon dectectors for particle detection, beam flux monitoring and dosimetry in high-dose radiation environment

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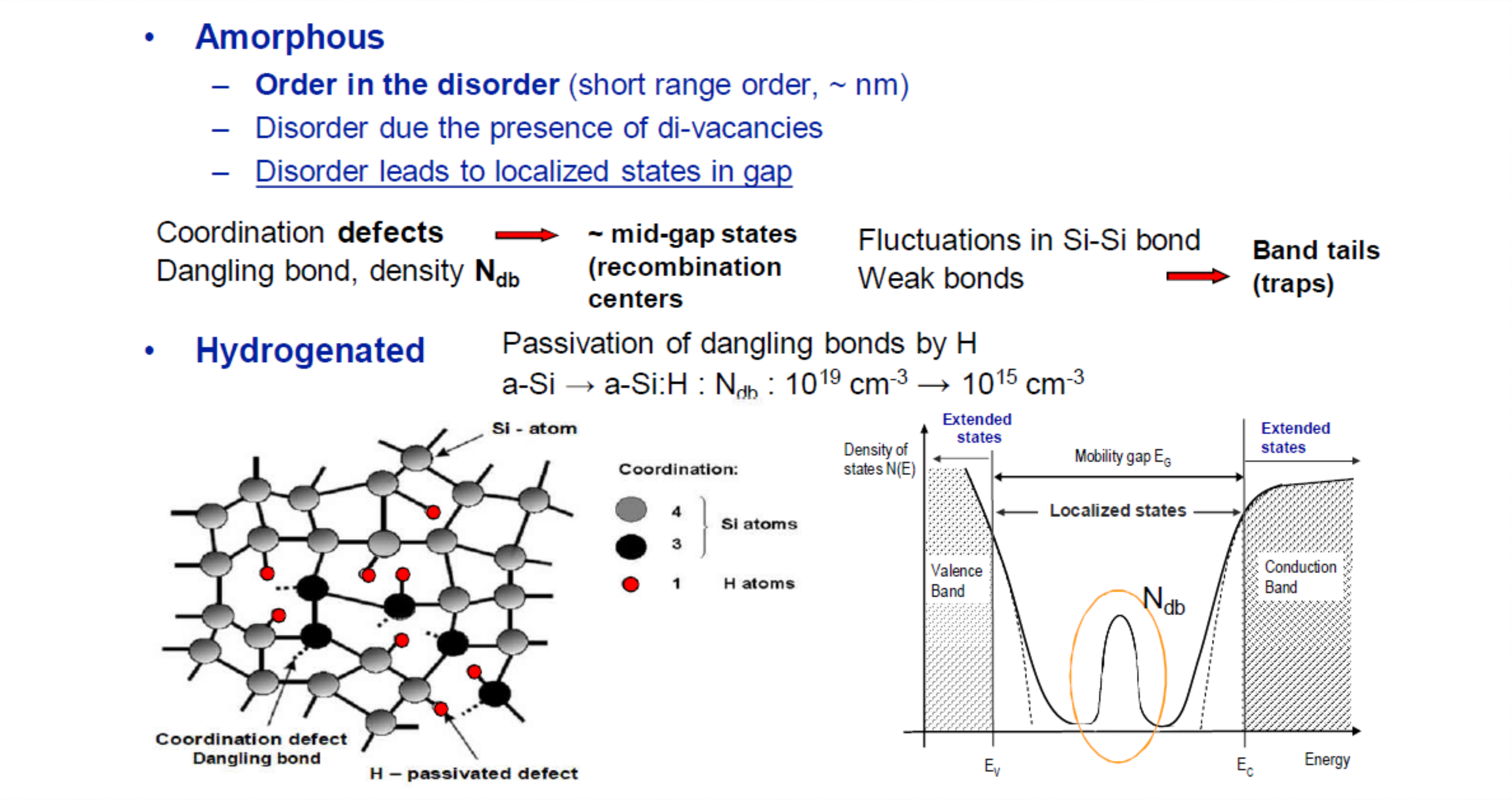
Hydrogenated Amorphous Silicon a-Si:H

- The first study on a-Si:H was reported by Chittik et al. in 1969
- Material was obtained by plasma-enhanced vapor deposition (PECVD) of SiH_4 (Silane) + Hydrogen.
- Substantial progress of the a-Si:H technology were performed when Spear and Lecomber demonstrated that this material could be substitutionally doped (both in n and p-types); this led to the development of various types of electronic devices such as transistors, solar cells, memories and eventually, in the second half of the 80', planar radiation detector in p-i-n structures.

A-Si:H Structure and density of states



- **Amorphous**
  - **Order in the disorder** (short range order, ~ nm)
  - Disorder due the presence of di-vacancies
  - Disorder leads to localized states in gap

Coordination **defects** → **~ mid-gap states (recombination centers**
Dangling bond, density $\mathbf{N_{db}}$

Fluctuations in Si-Si bond
Weak bonds → **Band tails (traps)**

- **Hydrogenated** Passivation of dangling bonds by H
  a-Si → a-Si:H : N_{db} : 10^{19} cm^{-3} → 10^{15} cm^{-3}

A-Si:H planar detectors pros & cons I

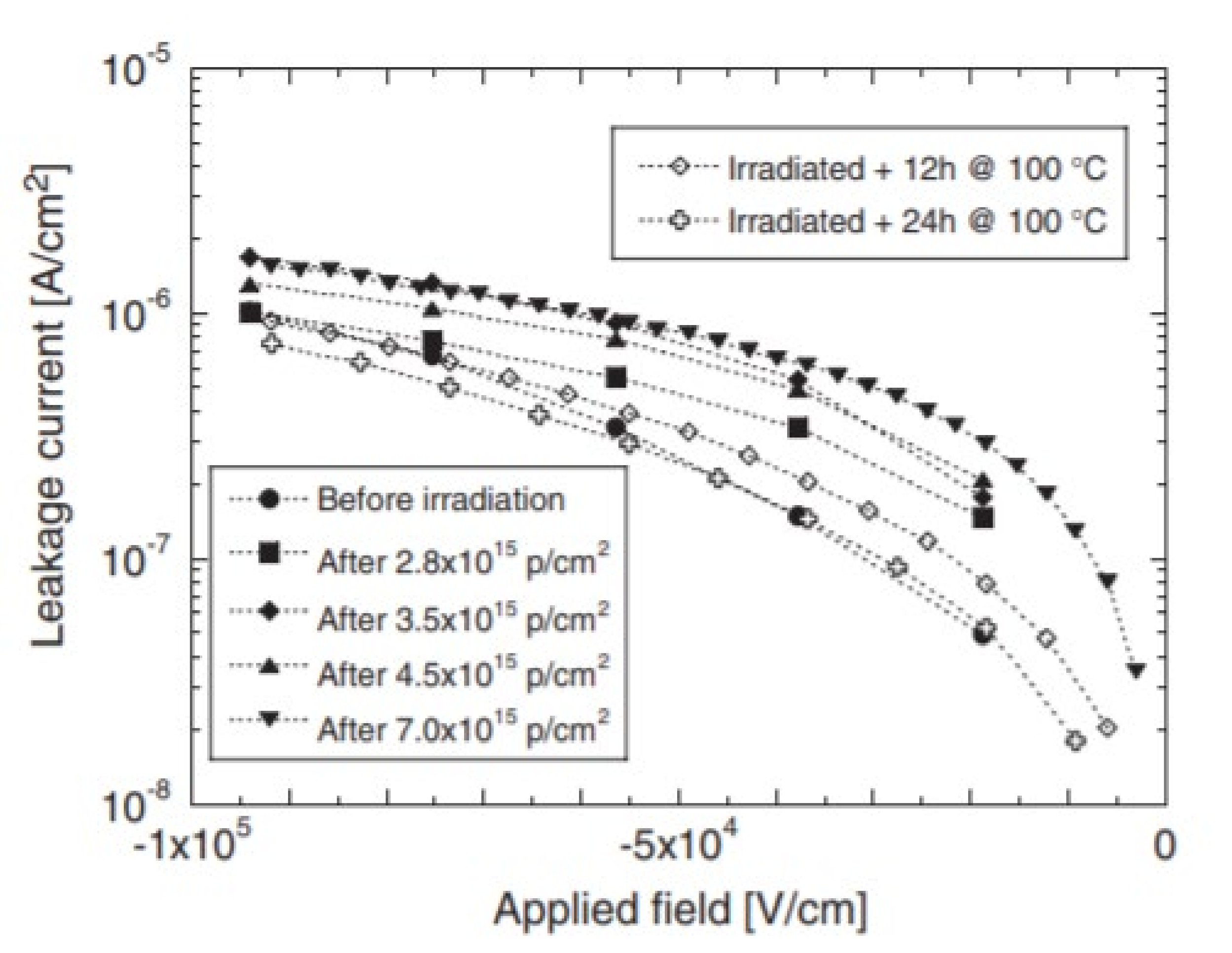
- Pros:
  - Extremely low radiation damage.
  - Low cost production (this technology is currently used in solar cells production)
  - Possible deposition in many different substrate materials

A-Si:H planar detectors pros & cons II

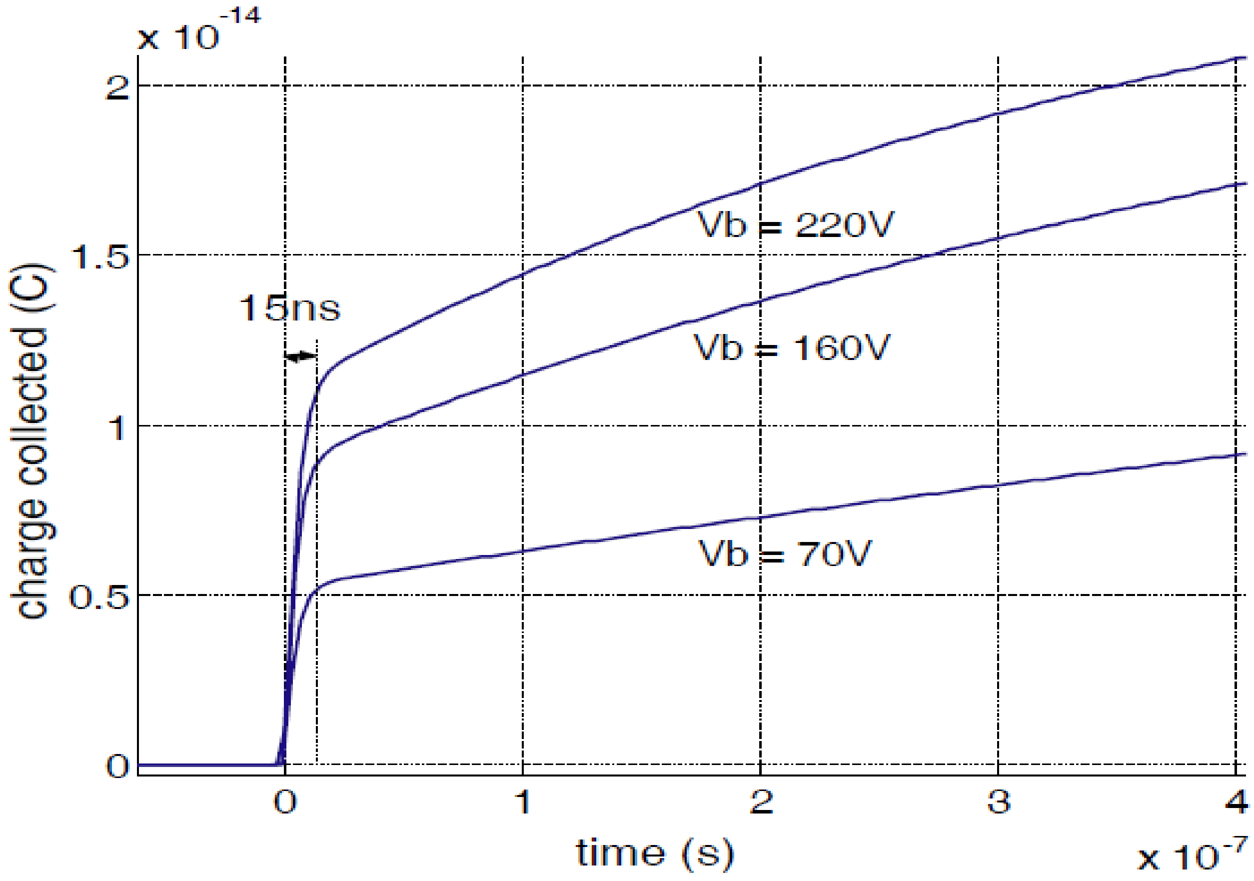
- Cons
  - High depletion voltage (about 1100 V for 50 um thickness)
  - Growth on a non-removable substrate

  - Pretty low charge collection efficiency: 50%(on a 30 um thick detector) energy to create a e-h pair similar to crystalline silicon (3.4-3.5 eV)
  - High leakage current (in the order of few uA/cm^2 on a 30 um detector)
  - Low mobility (from 1 to 10 cm^2 /Vs for electrons 2 orders of magnitude less for holes)
  - Limited thickness of substrates (max 100-150 um)

Displacement damage on a 30 um a-Si:H planar detector



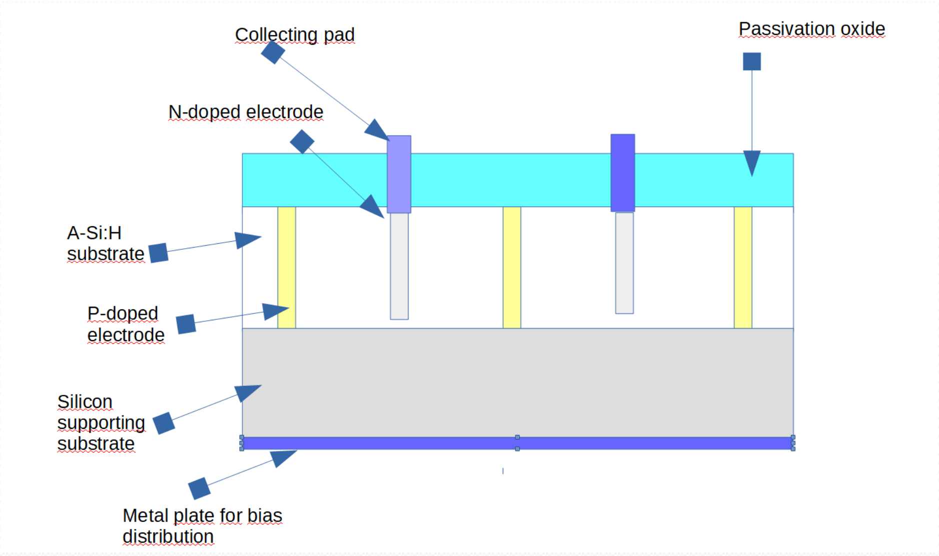
Signal formation on planar a-Si:H detectors



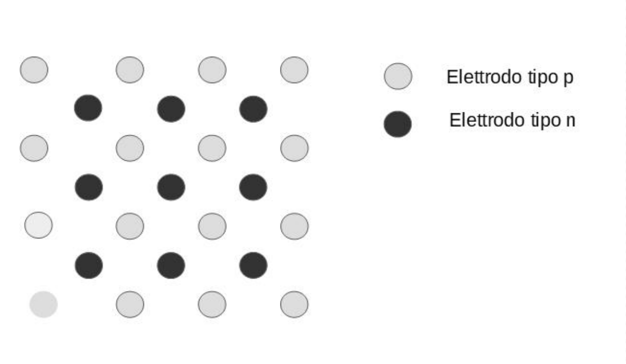
3D technology on a-Si:H

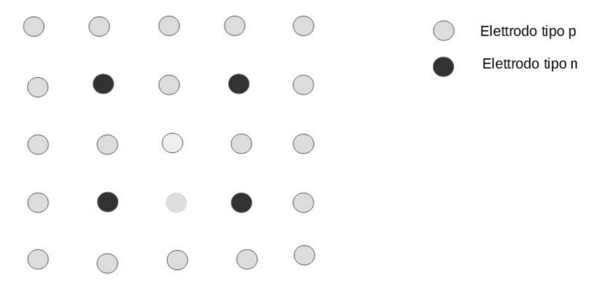
- The depletion potential applies on the interelectrode distance that is not coincident with the thickness of the detector
- Never attempted before
- Noise reduction test at cold temperature (e.g. -30°C)

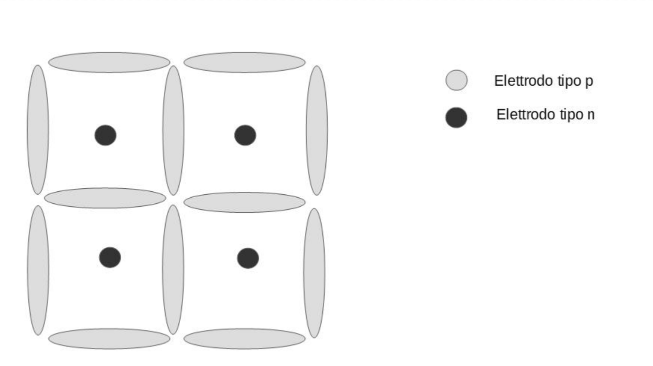
Baseline 3D detector structure

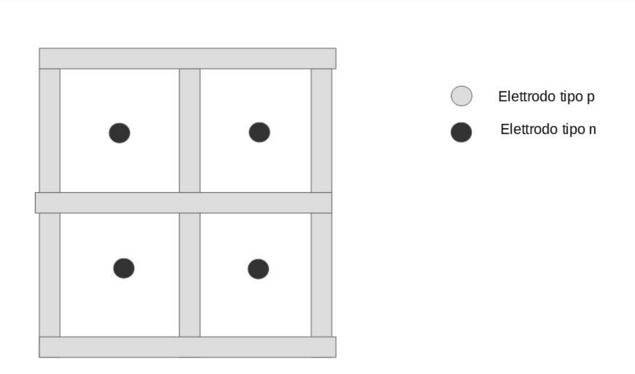


Possible 3D detector configurations









Technological options for doping the electrodes

- Option 1: Selective layers of metal oxide deposited via ALD
- Option 2: Ion implantation and low temperature activation (250 °C or below)

Prototype development

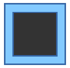
- Phase 1: construction of planar diodes with option 1 and 2 doping techniques.
- Phase 2: Construction of basic 3D structures in order to test the two proposed doping techniques.
- Phase 3: Construction of 3D detectors in various configurations.

Diodes and test structures layout in phase 1 prototypes

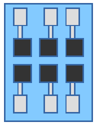
- Before depositing a-Si:H the p-type silicon wafer is devided in two halves and in one of the two halves is oxidated.
- In the non-oxidated half vertical diodes are built
- In oxidated half lateral diodes are built

Vertical diodes

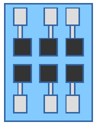
- 56x V_diode_single
- 56x V_diode_single_new_bond_pad
- 44x V_diodes_array_2x3_large
- 36x V_diodes_array_2x3_large_no_bond
- 64x V_diodes_array_2x3_small
- 72x V_diodes_array_2x3_small_no_bond
- 20x V_diodes_array_2x10_large
- 20x V_diodes_array_2x10_large_no_bond
- 18x Vertical_8_diodes_5mm
- 18x Vertical_8_diodes_5mm_bond
- 18x Vertical_8_diodes_10mm
- 18x Vertical_8_diodes_10mm_bond



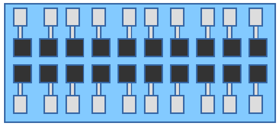
Single diode: 0.25 x 0.25 cmsq electrode
Surrounded by 1 mm frame of Si3N4



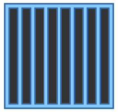
2 x 3 large diode array: 1 x 1 mmsq electrodes
Surrounded by 1 mm frame of Si3N4 bonding pads
200 x 200 um added (not in scale)



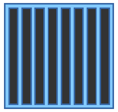
2 x 3 small diode array: 0.5 x 0.5 mmsq electrodes
Surrounded by 1 mm frame of SiN4 bonding pads
200 x 200 um added (not in scale)



2 x 10 large diode array: 1 x 1 mmsq electrodes
Surrounded by 1 mm frame of Si3N4 bonding pads
200 x 200 um added (not in scale)



Large 8 strips device: 10 x 0.5 mmsq electrodes
Surrounded by 0.5 mm frame of Si3N4 and 0.2 mm spacing
Covered by Si3N4



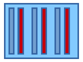
Small 8 strips device: 5 x 0.2 mmsq electrodes
Surrounded by 0.25 mm frame of SiN4 and 0.1 mm spacing
Covered by Si3N4 (different scale)

Lateral diodes

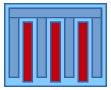
- 48x L_diode_comb_o_2x5_10um
- 48x L_diode_comb_o_2x5_20um
- 52x L_diode_comb_o_2x5_30um
- 50x L_diode_double_comb_o_2x5_10um
- 46x L_diode_double_comb_o_2x5_20um
- 68x L_diode_double_comb_o_2x5_30um
- 26x L_diode_array_o_2x5

- 100x Dosimetry_diode_20um_240um
- 100x Dosimetry_diode_30um_260um

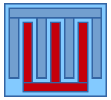
🟥 n-type electrode 🟦 p-type electrode



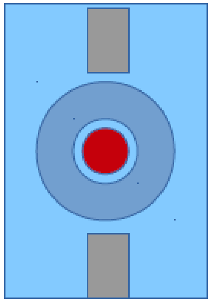
1 x 5 lateral diode array: 0.2 x 5 mmsq electrodes
Spacings of p-to-n electrode of 30 um or 20 um or 10 um
(3 versions not to scale in the figure) 1 mm distance
Between consecutive p-type electrode Surrounded by 1 mm
frame of Si3N4 that also fills the gap between electrodes



Comb-like diode: 0.2 x 5 mmsq n-type electrodes, 0.2 x 5 mmsq
Vertical p-type electrodes, 0.5 mm wide horizontal p-type
electrode of Length >1.4 mm)
Spacings of p-to-n electrode of 30 um or 20 um or 10 um
(3 versions not to scale in the figure) Surrounded by 1 mm
frame of SiN4 that also fills the gap between electrodes

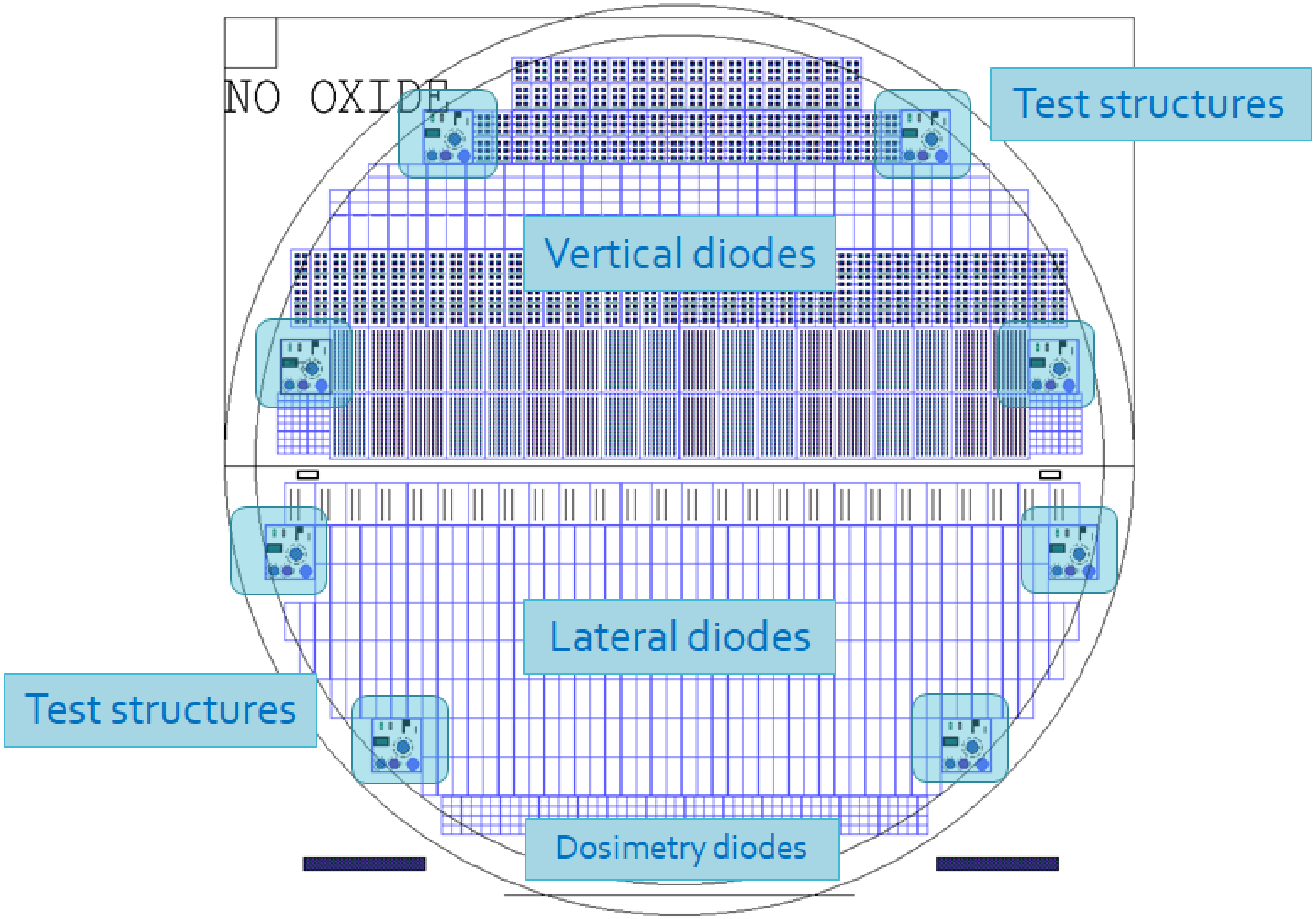


Double Comb-like diode: 0.2 x 5 mmsq vertical n-type electrodes,
0.5 mm wide horizontal n-type electrode with length > 1 mm.
0.2 x 5 mmsq Vertical p-type electrodes, 0.5 mm wide horizontal
p-type electrode of Lenght >1.4 mm
Spacings of p-to-n electrode of 30 um or 20 um or 10 um
(3 versions not to scale in the figure) Surrounded by 1 mm
frame of Si3N4 that also fills the gap between electrodes



Dosimetry optimized diode: 100 um diameter of the central n-type
Electrode, 10 um or 20 um or 30 um intergap distance 220 or
240 or 260 um external diameter p-type electrode, two metal
Bonding pads 50 x 100 umsq. The light blue area is the Si3N4
Passivation layer. This basic configuration will be arranged in a
20 x 20 array

Final complete Layout



Test structures

Vertical diodes

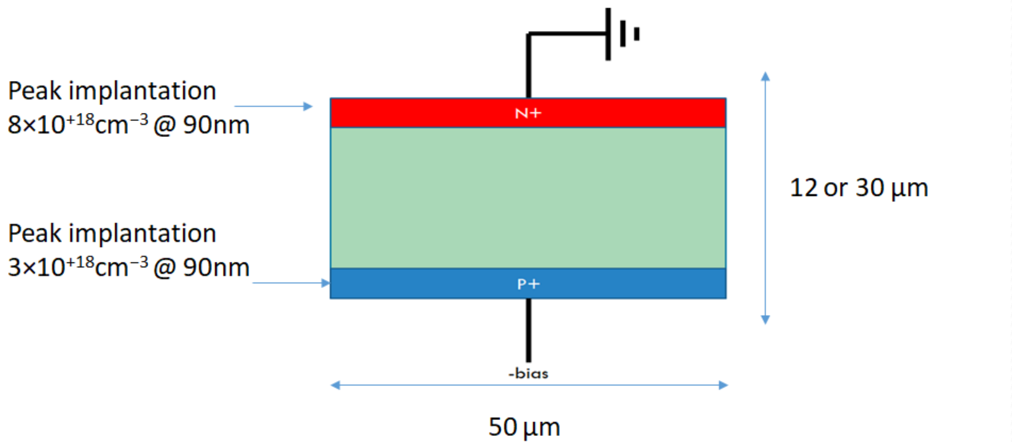
Lateral diodes

Test structures

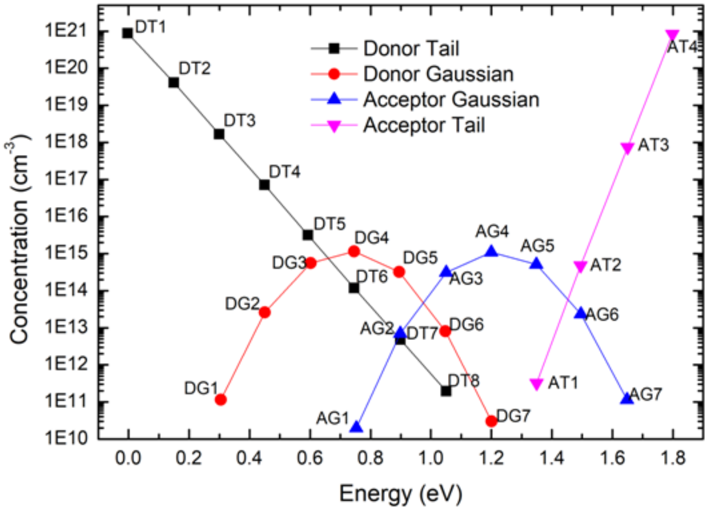
Dosimetry diodes

A-Si:H material simulation

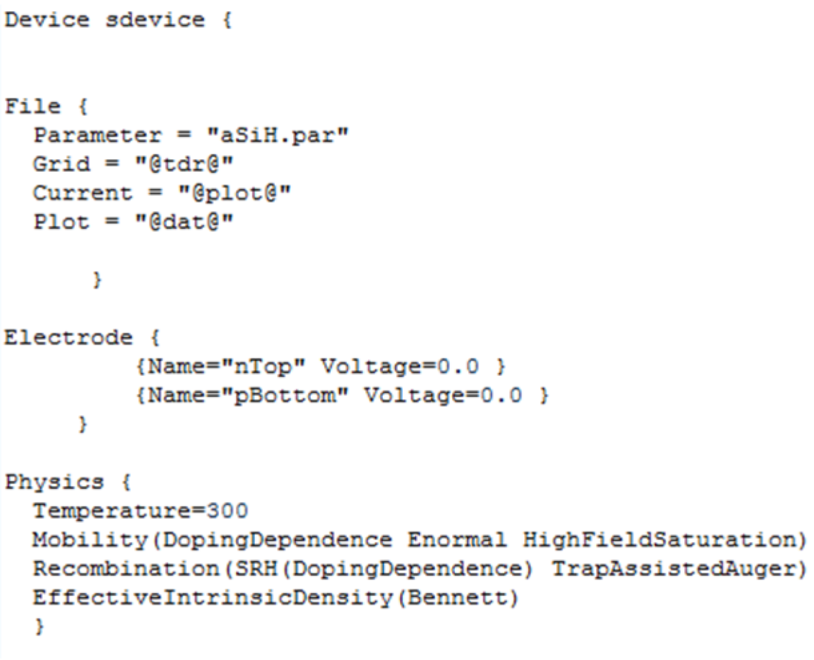
Parameter (units)	Literature	Simulation
Relative permittivity	11.8-11.9	11.7
Electron mobility ($cm^2\ V^{-1}\ s^{-1}$)	0.5-20	10
Hole mobility ($cm^2\ V^{-1}\ s^{-1}$)	0.003-10	0.01
Band Gap (eV)	1.7-1.9	1.84
Dangling bond density (cm^{-3})	$5 \times 10^{14} – 5 \times 10^{16}$	4×10^{15}
Activation energy (eV)	0.42-0.49	0.52



Defects model

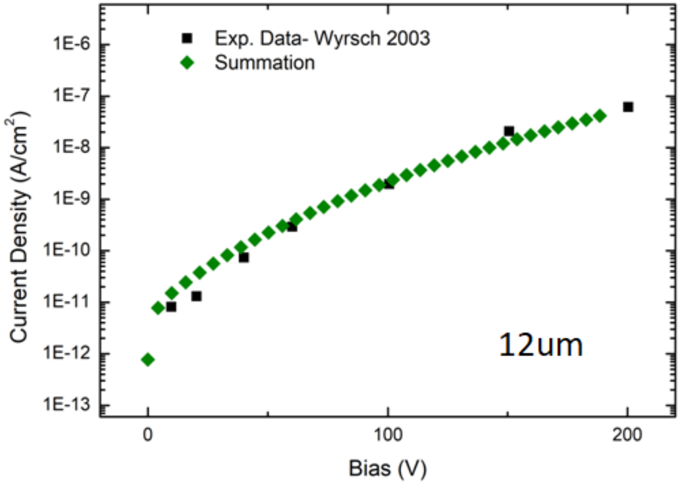


Trap type	Introduction factor
DTi	0.001
DGi	1
AGi	5
ATi	0.001



```
Device sdevice {


File {
  Parameter = "aSiH.par"
  Grid = "@tdr@"
  Current = "@plot@"
  Plot = "@dat@"

      }

Electrode {
         {Name="nTop" Voltage=0.0 }
         {Name="pBottom" Voltage=0.0 }
     }

Physics {
  Temperature=300
  Mobility(DopingDependence Enormal HighFieldSaturation)
  Recombination(SRH(DopingDependence) TrapAssistedAuger)
  EffectiveIntrinsicDensity(Bennett)
  }
```

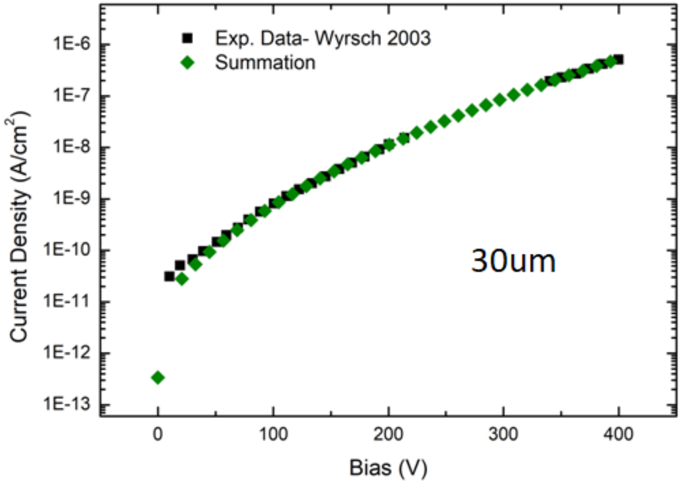
Simulated leakage current density



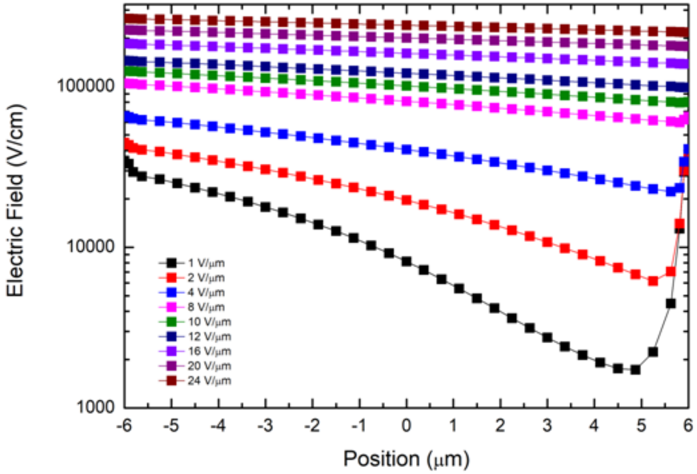
Current density simulated by TCAD is combined with the current density model due to Pool-Frenkel pair generation which is described by a dependency to the square root of the electric field (sqrt(E)).

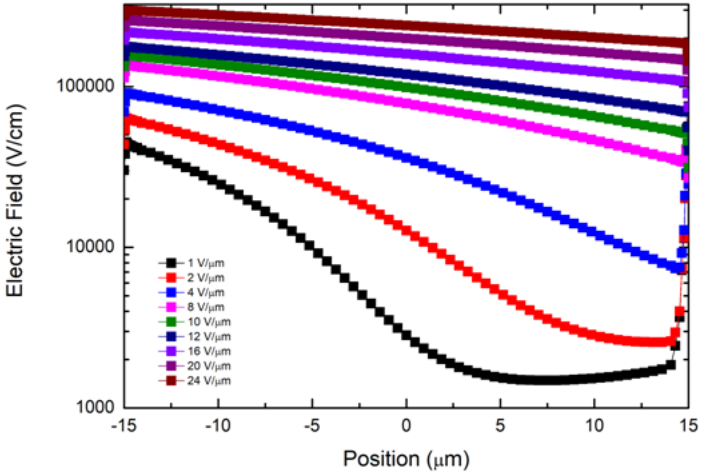
The model proposed scales appropriately with the thickness of the detector intrinsic layer as proved by comparison with experimental data obtained by Wyrsh et al. (2003).

$$J = a * \exp^{\sqrt{E}*b_0*\sqrt{d}} + \exp^{-\frac{E_0}{kT}}$$



Electric field vs thickness

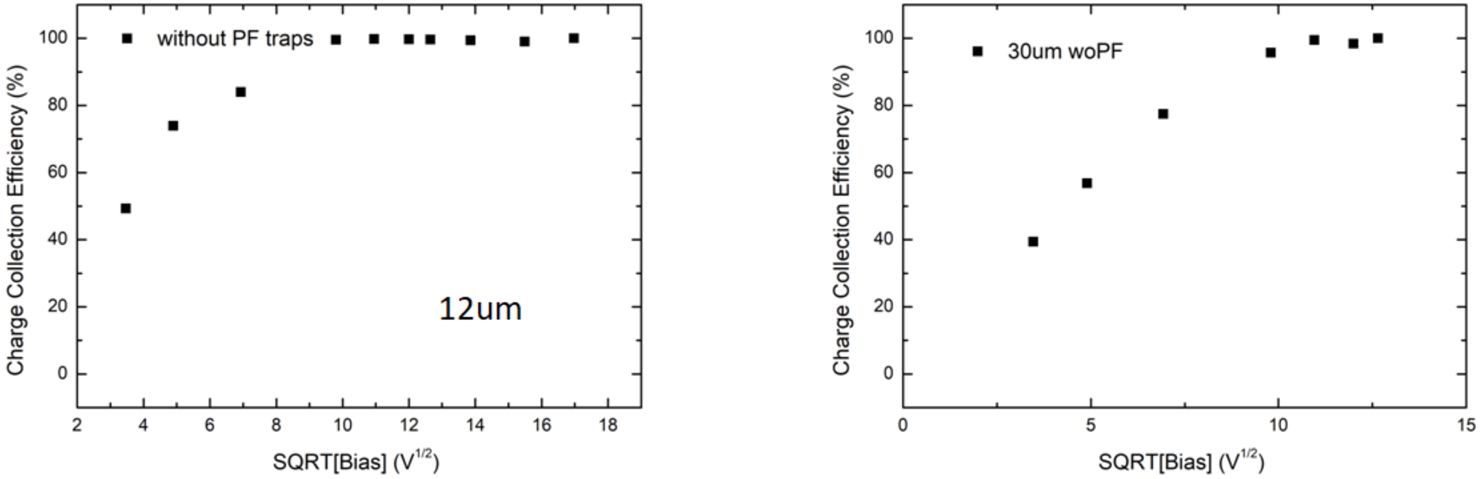




Electric field simulated by TCAD predicts a depletion layer growing in the intrinsic layer with 6 $V.um^{-1}$ and 11 $V.um^{-1}$ for full depletion of 12 and 30um thicknesses, respectively.

This is comparable (within 10% deviation) with the data obtained experimentally by Despiesse et al 2008 on samples with similar geometry.

Charge collection efficiency



Charge collection efficiency simulated using a MIP of 80 e/h.um^{-1} confirm the full depletion at approx. 69V for a 12um device and 400V for a 30um device.

Ministero dello Sviluppo Economico

Ricevuta di presentazione

per

Brevetto per invenzione industriale

Domanda numero: 102018000010735

Data di presentazione: 30/11/2018

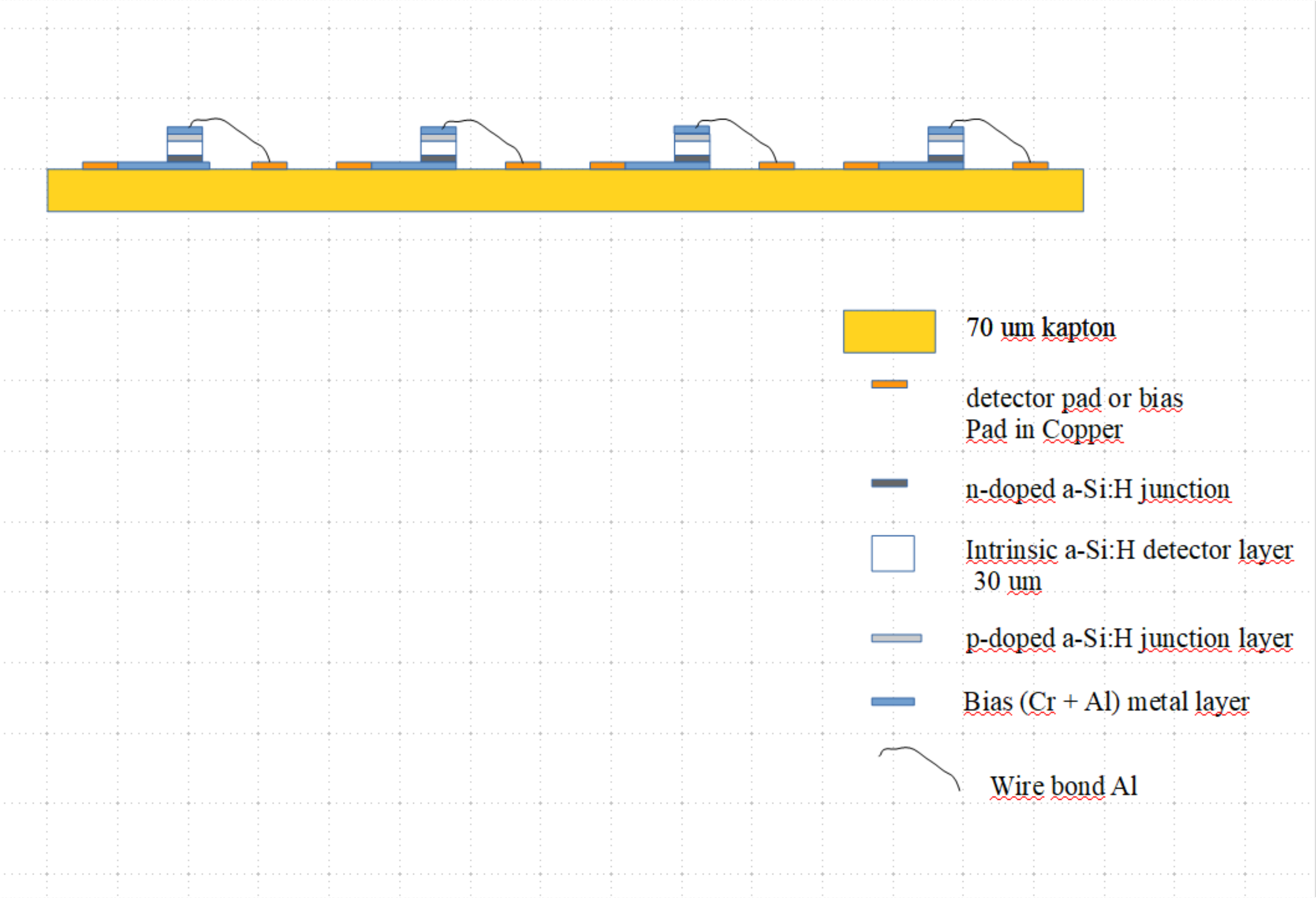
Timeline of the 3 years program

- Tape out of the phase 1 prototype. DONE
- Completion of production of the phase 1 prototype by January at most.
- Testing of the phase 1 prototype and beginning of definition of the phase 2 prototype by april 2020
- Construction of phase 2 prototype by mid 2020.
- Testing of phase 2 prototype and design of the phase 3 prototype by the end of 2020
- Production and testing of the phase 3 prototype by the end of 2021

Testing x-ray dosimetry with prototypes

- We are going to test dosimetry planar devices with x-ray to evaluate their capability as dosimeters.
  - Linearity
  - Dependance on direction of dose evaluation.
  - Deposition on kapton (adhesive) to explore the possibility to have dosimeters that can be attached to the body

Planar detectors for beam dosimetry



70 um kapton

detector pad or bias
Pad in Copper

n-doped a-Si:H junction

Intrinsic a-Si:H detector layer
30 um

p-doped a-Si:H junction layer

Bias (Cr + Al) metal layer

Wire bond Al

The future of 3D a-Si:H detector

- Construction of an actual pixel detector bump-bonded on a readout chip.
- Deposition of a-Si:H directly on the readout chip and construction of the 3D detector on the deposited substrate.