Design, Fabrication, and preliminary test results of a new inverse-LGAD for soft X-ray Detection

Ozhan Koybasi, Angela Kok, Marco Povoli (SINTEF)

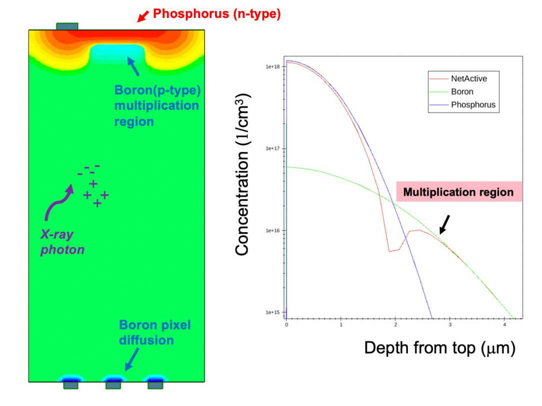
Julie Segal*, Chris Kenney (SLAC)

U.S. DEPARTMENT OF ENERGY | Stanford University | SINTEF | SLAC NATIONAL ACCELERATOR LABORATORY

Thin Entrance Window LGADs

- To exploit the unique scientific imaging opportunities at the new XFELs, we need pixel detectors that can detect soft X-rays with energies as low as 250 eV
- Low Gain Avalanche detector could improve signal-to-noise for soft x-ray sensors, with good spatial resolution, *however,* the conventional LGAD structure is not compatible with thin-entrance window (<50nm)
- Lack if thin entrance window is a limiting factor for using LGADs for other applications, such as detection of the following:
  - UV light from noble liquid scintillation
  - Low energy electrons in reaction microscopes
  - Ion products from nuclear fusion
  - Soft x-rays for heliophysics

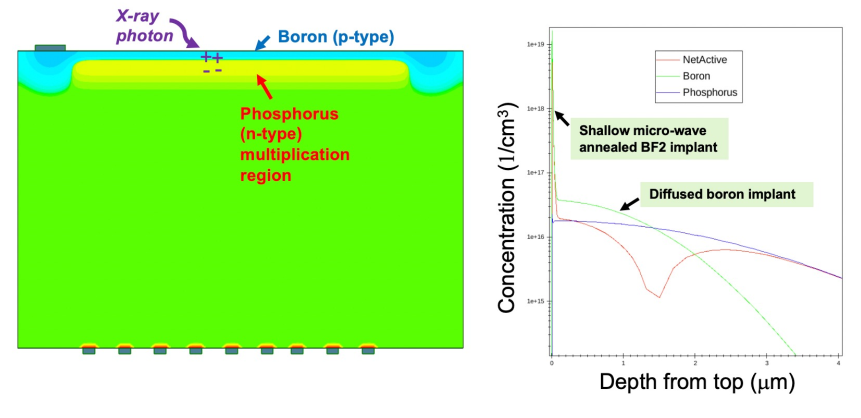
New Shallow-Entrance Window LGAD Concept



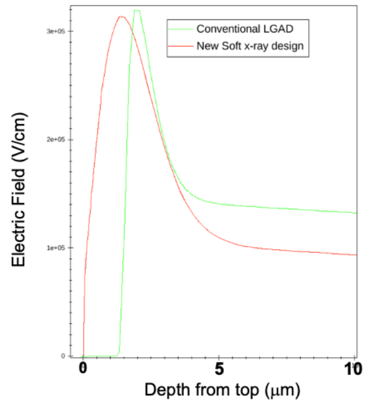
Conventional LGAD Structure (cross-section, not to scale)
- **Not compatible with shallow entrance window**

Thin-entrance window LGAD Structure

- **Polarity of dopants is reversed so that electrons drift toward gain region (electron ionization coefficient much higher than for holes)**
- **Boron profile created by *two separate implant steps***
  - **(1) Conventional diffused profile**
  - **(2) Shallow surface implant activated with micro-wave anneal**
- **Under bias, the diffused boron profile is completely depleted, resulting in electric field extending to silicon surface**



Thin entrance window LGAD (process simulation)



Simulated Electric field profiles for LGADs under bias

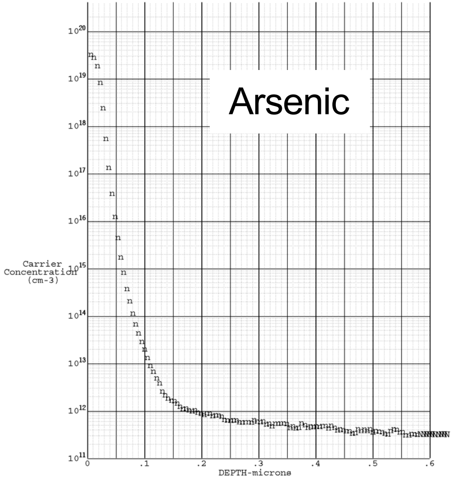
J. Segal and C. Kenney, "New Thin-Entrance Window LGAD for Soft X-ray Detection at LCLS-II", 2020 IEEE Nuclear Science Symposium

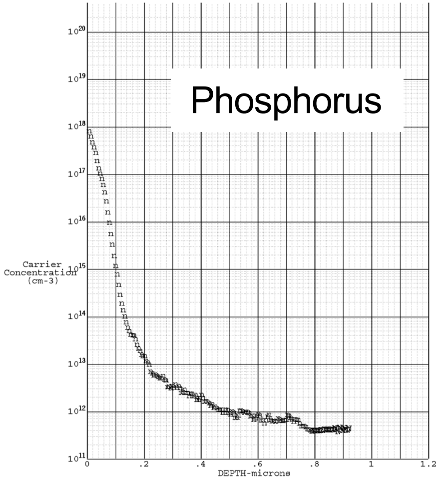
Microwave anneal for thin entrance windows

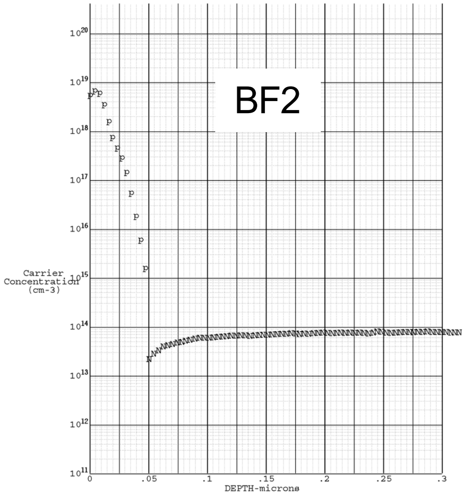
- Shallow entrance window is an important challenge for realizing sensors for soft x-ray low energy electrons, low energy ions, and UV light
- Microwave annealed (MWA) entrance window process for fully depleted high resistivity sensors was first proposed in 2018
- Enables dopant activation without high temperature
  - Activates dopant without driving profile deeper → create **shallow entrance window**
  - No damage to existing structures → we can post-process the backside of foundry processed planar or CMOS sensors
- Fast and cost effective

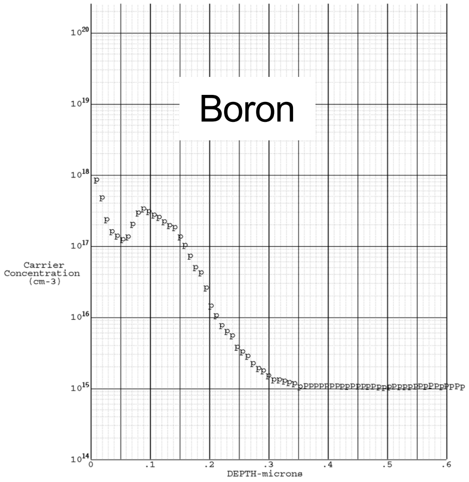
Axom microwave anneal tool in SLAC cleanroom

Dopant Activation with Microwave Anneal (MWA)





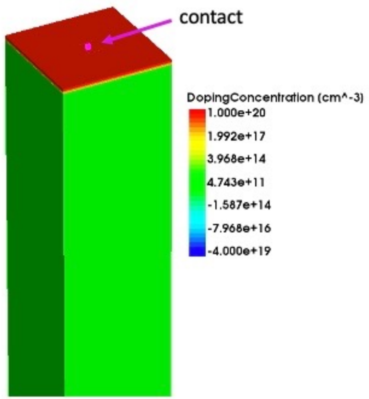


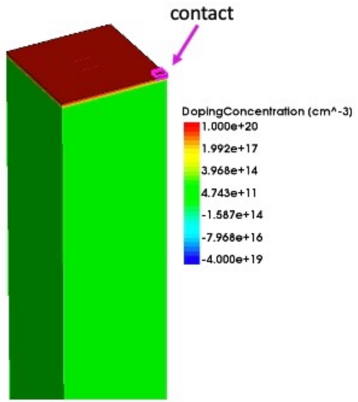


- **Spreading resistance profiles (SRP) on implanted test wafers show dopant activation after MWA, both n-type and p-type dopants**
- **Arsenic and BF2 result in the shallowest profiles**

TCAD Simulations of Entrance window: Summary

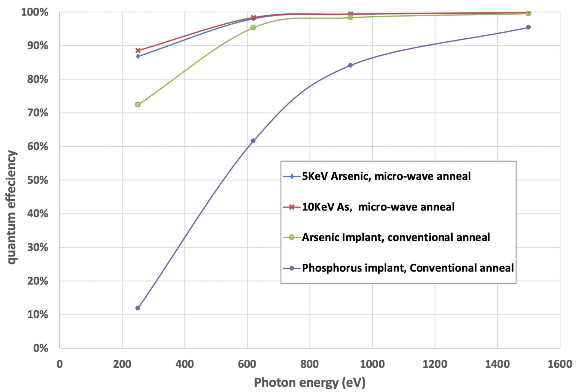
- We studied the quantum efficiency for various dopant profiles using TCAD device simulations
- Results:
  - Surface recombination is important for shallow entrance windows
  - Electric field profile is important
  - Electric field depends on dopant profile steepness as well as depth



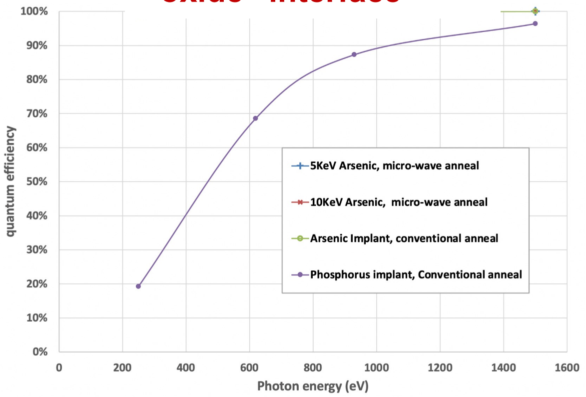


QE vs. photon energy

“metal” interface



“oxide” interface



J. Segal et al, "Thin-Entrance Window Process for Soft X-ray Sensors", Frontiers in Physics, section Radiation Detectors and Imaging, Feb 2021

Measured Quantum Efficiency vs. TCAD Simulation

Quantum Efficiency measured at ALS Calibrations and Standards Beamline by E. Gullikson

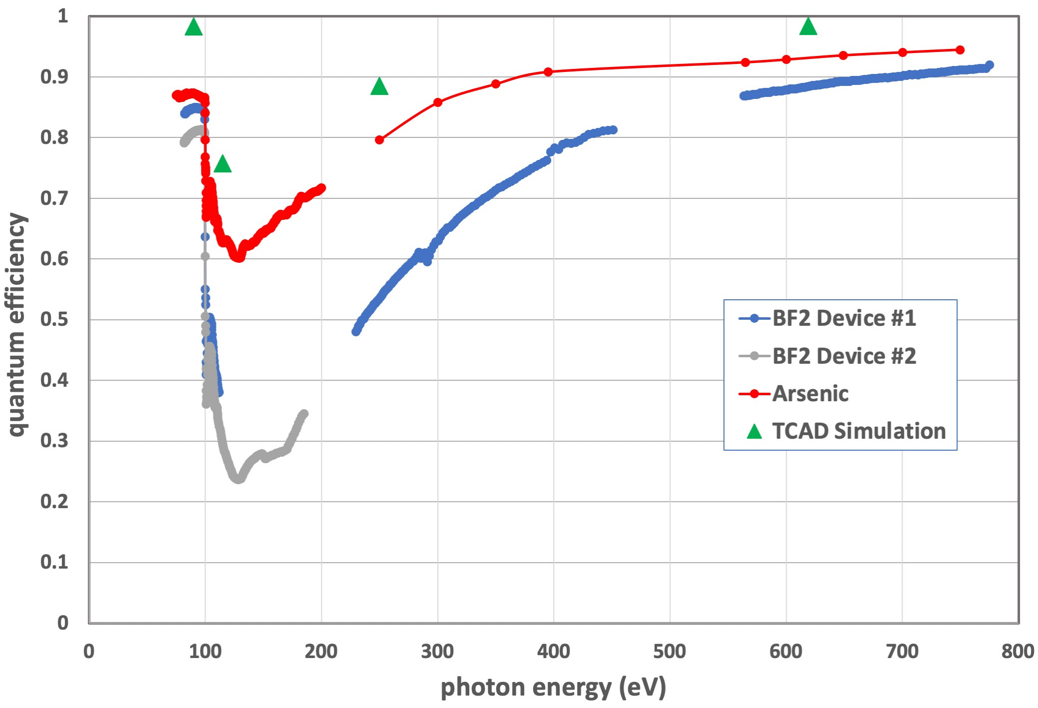
- Two types of microwave annealed surface contacts, BF2 and As

Why is there the discrepancy

- Between measurement and TCAD simulation?
- Between BF2 and Arsenic?

Possible explanations:

- Surface roughness, which is not in model
- Other process variation affecting surface recombination velocity
- TCAD model limitations near the interface

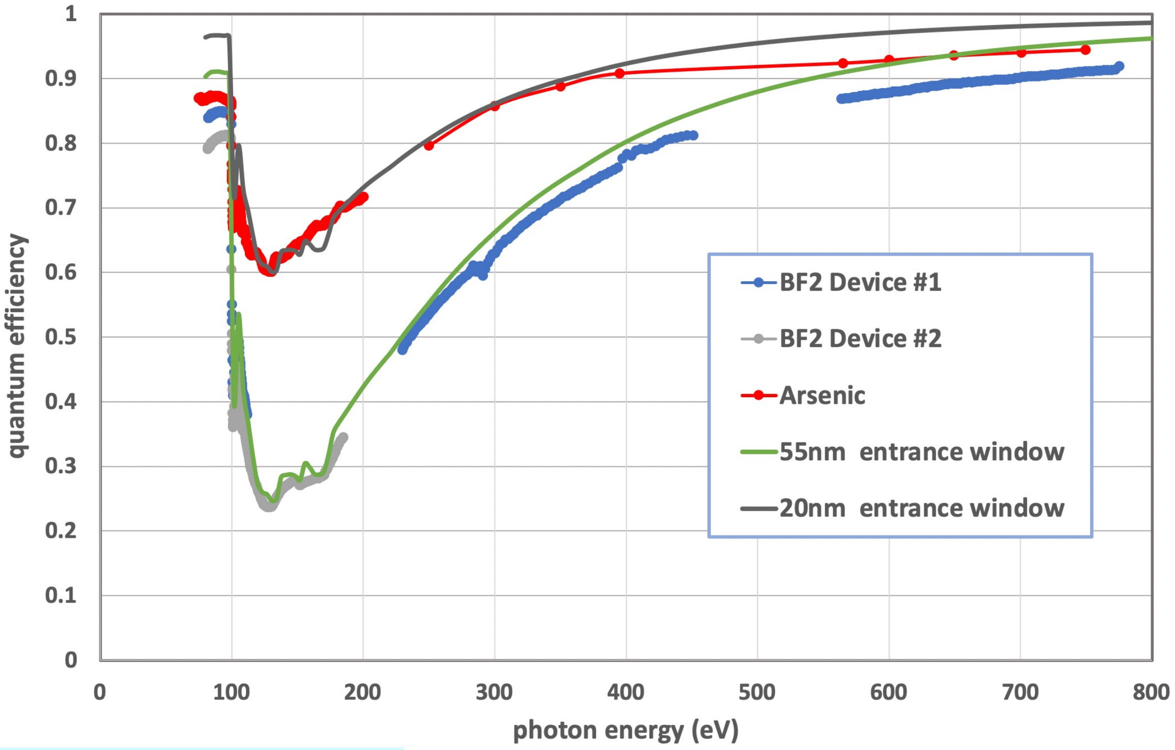


J. Segal et al "First Soft X-ray Quantum Efficiency Measurements on Microwave Annealed Thin-Entrance Window Sensors ", 2021 IEEE NSS/MIC

Measured Quantum Efficiency fit to Filter Transmission Model

QE measurements compared to simple “insensitive region” window model

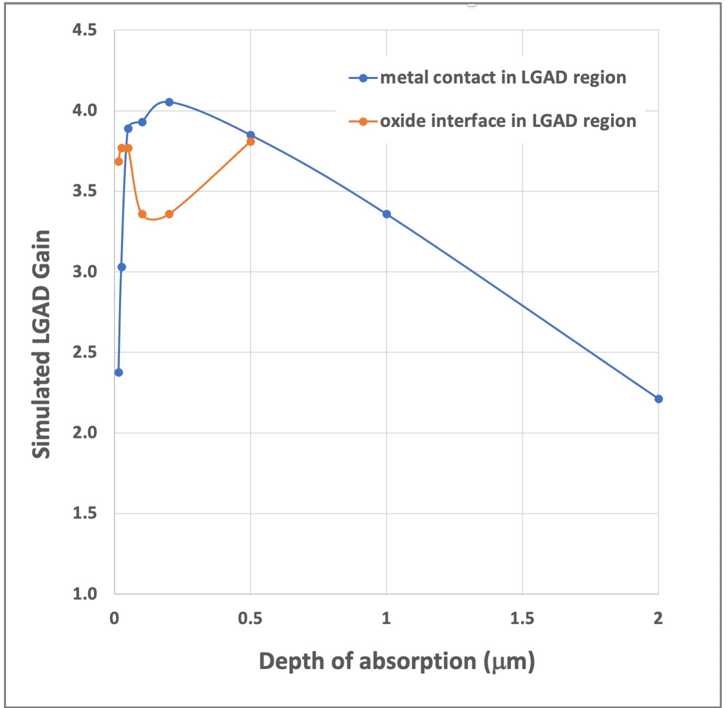
- Simple model assumes *no charge is collected* from photons absorbed in window region
- Arsenic window roughly equivalent to **20nm** insensitive region
- BF2 window roughly equivalent to **55nm** insensitive region



J. Segal et al “First Soft X-ray Quantum Efficiency Measurements on Microwave Annealed Thin-Entrance Window Sensors “, 2021 IEEE NSS/MIC

Simulation of Shallow Entrance window *LGAD*

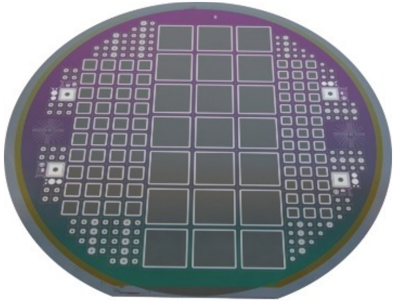
- Similar to previous work on simple diodes, compare “metal” contact to “oxide” contact
    - For LGAD, 2D simulation run instead of 3D simulation
- Result: Similar dependence on interface properties

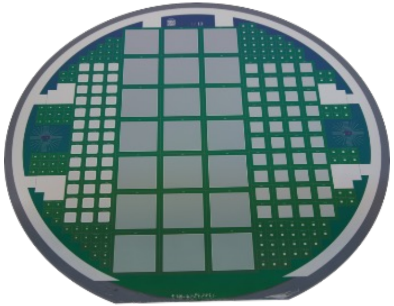


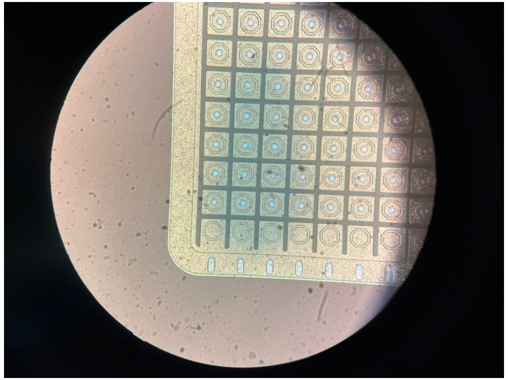
Simulated LGAD gain for soft x-ray LGAD for photons absorption from 15nm to 2□m from surface.

Shallow-Entrance Window LGAD Development

- SLAC and SINTEF partnered to implement the new shallow entrance window LGAD, wafers are now complete and preliminary testing complete
- Wafer layout includes
  - 100um pitch ”proto-type” size arrays for bump-bonding to SLAC ASICs
  - Single “pixels” for bench test, with and without gain layer
- Multiple implant splits, every wafer is unique
- Based on diode measurements with various LED’s, we estimate the gain for shallow absorption on the best wafer to be >= 7
- Bump processing underway in preparation for bump-bonding proto-type arrays to Tixel ASIC *, capable of sub 100pS timing resolution



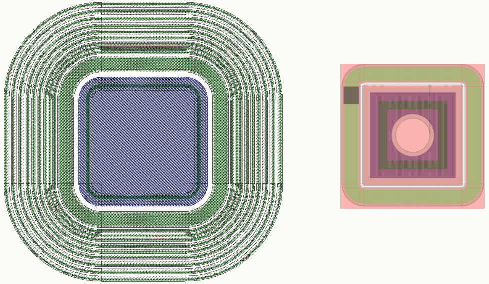




* B. Markovic et al, “Design and Characterization of the tPix Prototype: a Spatial and Time Resolving Front-end ASIC for Electron and Ion Spectroscopy Experiments at LCLS” , 2016 IEEE NSS/MIC

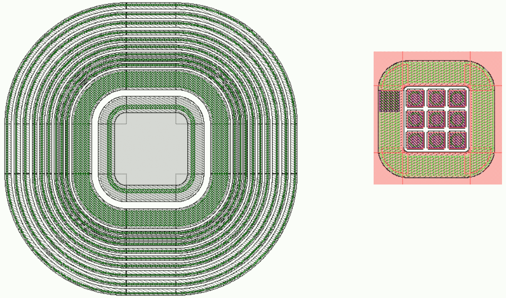
LGAD Design & Fabrication

Small pad diode for first tests



Window side Pad side

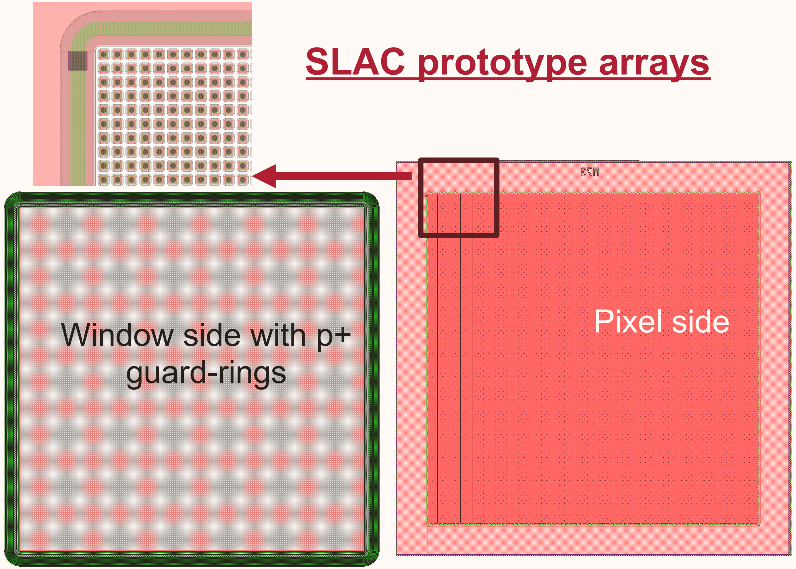
3 x 3 Pixel Sensor - easy assembly for testing



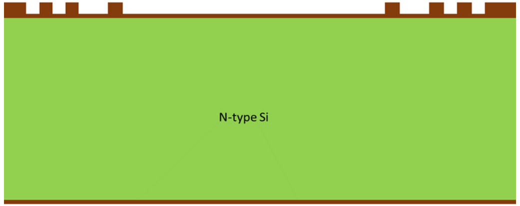
Window side Pixel side

- N-on-N technology
- P Spray for N+ isolation
- Window side: 7 mask layers
- Readout side: 4 mask layers
- Implantation using photoresist masks

SLAC prototype arrays

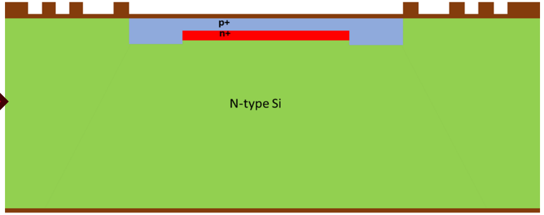


Fabrication Process Steps

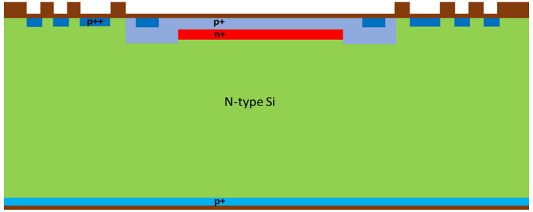


Window side:
- Oxidation
- Patterning of oxide for subsequent implantation steps

Window side:
- Gain layer implantation

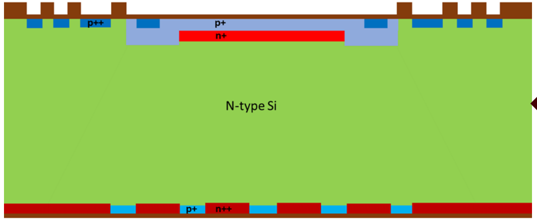


Window side:
- Deep boron implantation

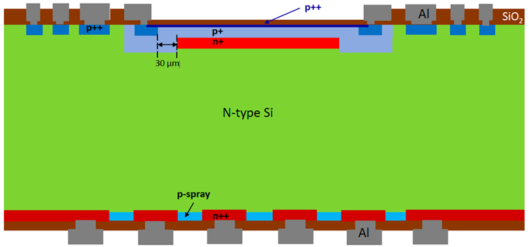


Window side:
- Guardring implantation

Pixel side:
- P-spray implantation



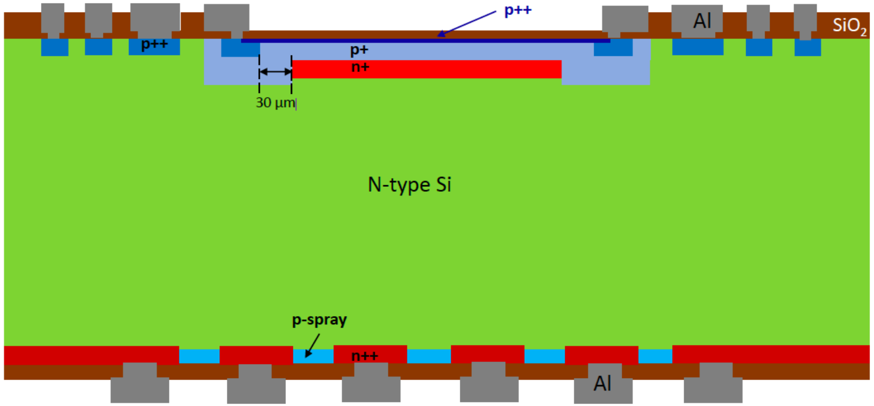
Pixel side:
- Pixel implantation



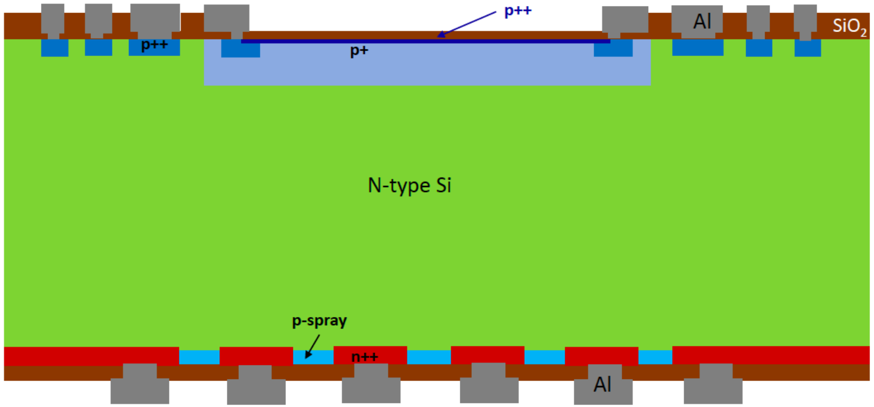
Final steps for both sides:
- Contact opening
- Metallization
- Passivation

Device cross sections: Diodes with and without gain layer

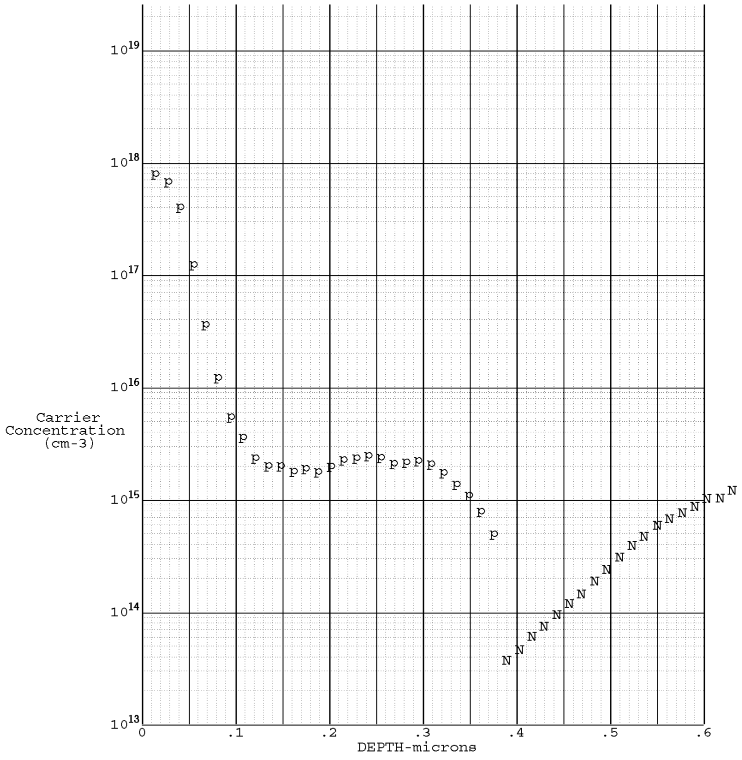
Device structure (with gain layer)

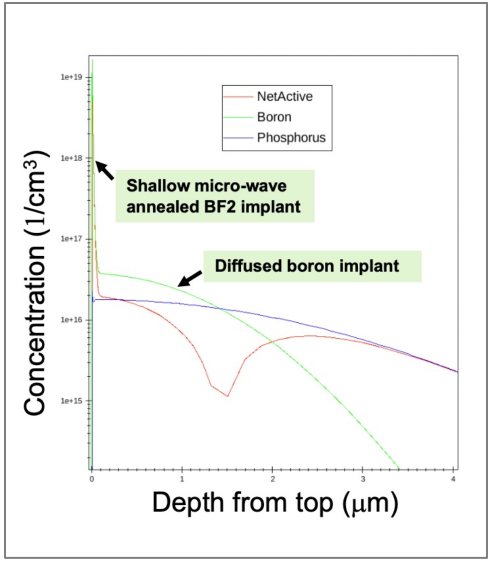


Device structure (without gain layer)



Spreading Resistance Profile on LGAD Gain Region

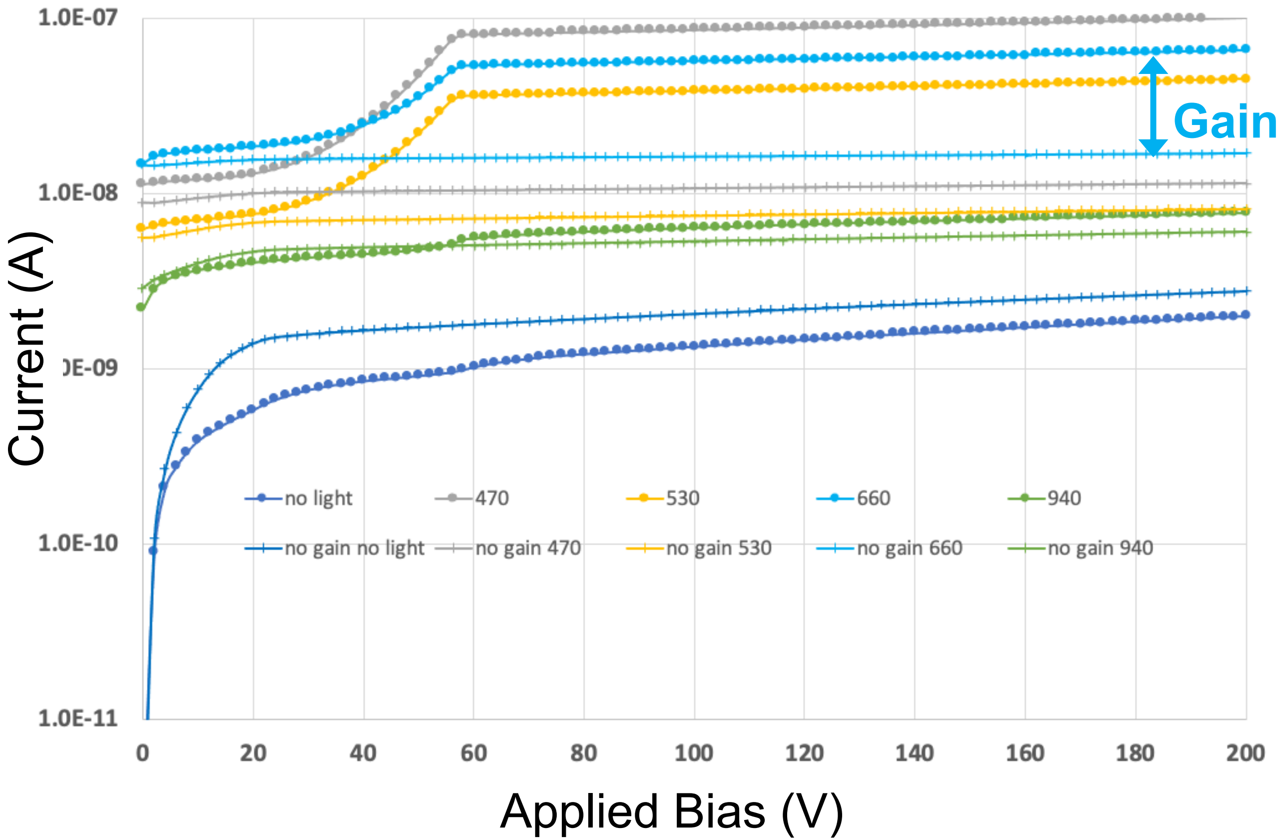




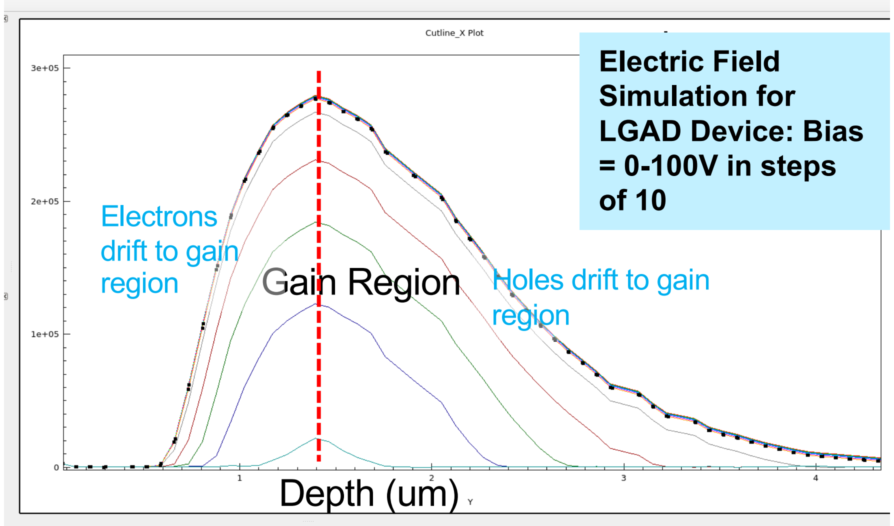
“Best” Shallow Entrance Window LGAD Wafer

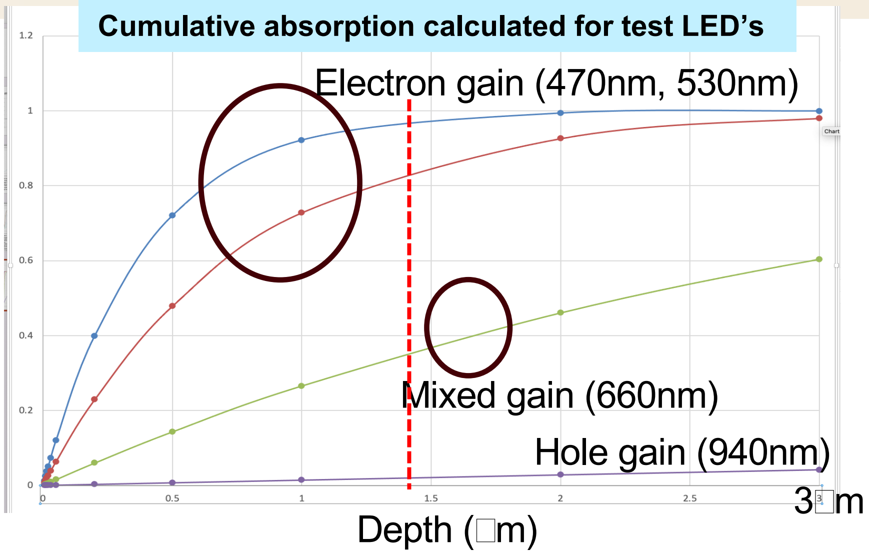
Measured IV curves

- Wafer level bench test
- On single diodes
- With and without gain layer
- With LEDs illumination at 470nm, 530nm, 660nm, and 940nm



Understanding Gain Measurements for Different Wavelengths, verification of gain for shallow absorption





If radiation is absorbed at <1.4um from the surface, gain will be due to electrons. For >1.4um, gain will be due to holes.

condition	Measured Gain	carriers
no light	1.4	mostly holes
microscope light	3.0	mixed?
470nm	6.9	electrons
530nm	4.8	more electrons
660nm	3.3	more holes
940nm	1.4	holes

Conclusions

- Promising results seen on first process development run of new shallow entrance window LGAD, gain = 7.0 for best wafer
  - Wafer-level bench test results shown today
  - Single pixel with and without gain layer
  - LED illumination at 4 different wavelengths to characterize gain vs. depth
- Prototype size pixel array LGAD sensor bump-bonded to fast ASIC – in preparation
- Future runs planned for optimization
  - Improved gain
  - Refinement of entrance window process