3D Doping Concentration Imaging of Silicon Pixel Sensors Using Backside Pulsing

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Doping, The Basis of Semiconductor Technology

Distribution of dopants determines critical properties of silicon sensors, such as depletion voltage and charge collection properties.

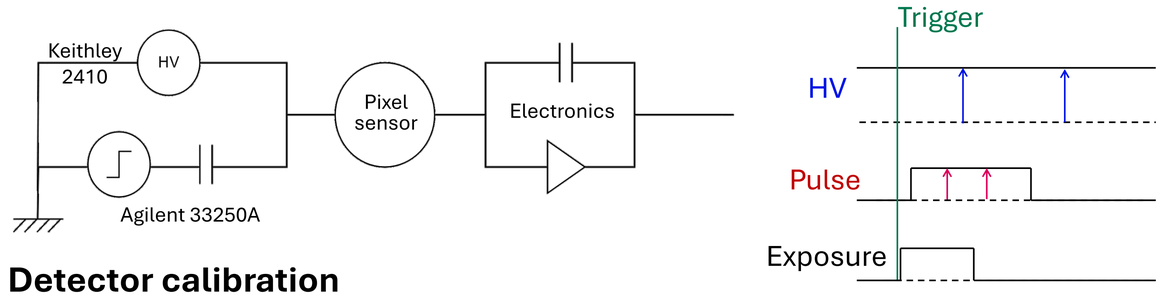
Silicon sensors used in high-energy physics and photon science usually feature high resistivity/low doping concentration of $10^{11} - 10^{12}$ cm^{-3}.

For these sensors, conventional doping measurement methods face significant limitations as listed below:

Methods:	C-V profiling	Spread Resistance (SR)	Secondary Ion Mass Spectrometry (SIMS)
Granularity	Coarse	Coarse	Fine
Doping range	Wide	Wide	Higher doping
Probing area	Large	Small	Small
DUT integrity	Non-destructive	Destructive	Destructive

We have developed a novel method to image 3D doping concentration of silicon sensors bump-bonded to readout chips, based on the backside pulsing technique [1]. This approach offers fine granularity, large area coverage, and a wide doping range.

Experimental Setup Based on Backside Pulsing



Detector calibration

- Constant bias voltage above depletion, e.g., 150 V
- Scanning pulse height: $Q_{\mathrm{pix}} = C_{\mathrm{pix}} V_{\mathrm{pulse}}$
  - $C_{\mathrm{pix}} = \epsilon A / Z$, Z sensor thickness, A pixel area; fC level
  - V_{pulse} up to ~10 V covers the dynamic range
- Generating pixel-wise ADU to energy LUT

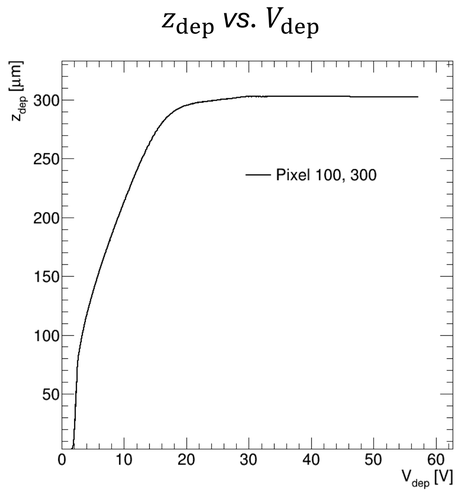
3D doping concentration imaging

- Scanning bias voltage from close to zero to above depletion
- Adjustable pulse height to avoid saturation

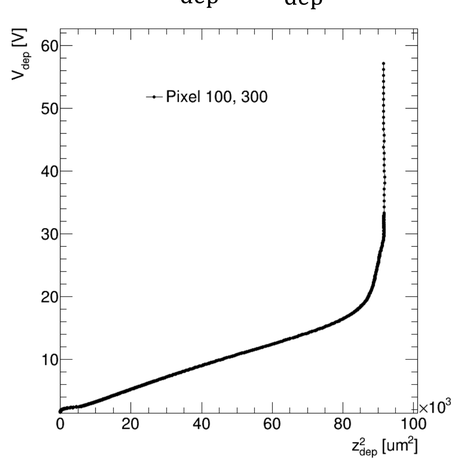
Analysis

1. Get charge Q integrated by each detector pixel converting the raw output using energy calibration
2. Get depletion depth $z_{\mathrm{dep}} = \epsilon A / C = \epsilon A V_{\mathrm{pulse}} / Q$
   - Planar assumption
3. Local doping concentration extraction
   - Depletion voltage $V_{\mathrm{dep}} = \int_0^{z_{\mathrm{dep}}} z \cdot \frac{n(z) e}{\epsilon} dz$
     - z: depth from the pixel side
     - $n(z)$: doping concentration
   - $n(z) = \frac{dV_{\mathrm{dep}}}{dz_{\mathrm{dep}}} \frac{\epsilon}{z_{\mathrm{dep}} e} \approx \frac{\epsilon}{e} \frac{1}{z_{dep}} \frac{\Delta V_{\mathrm{dep}}}{\Delta z_{\mathrm{dep}}} = \frac{2\epsilon}{e} \frac{\Delta V_{\mathrm{dep}}}{\Delta z_{\mathrm{dep}}^2}$
     - $\frac{\Delta V_{\mathrm{dep}}}{\Delta z_{\mathrm{dep}}^2}$ estimated using linear fitting every 10 µm

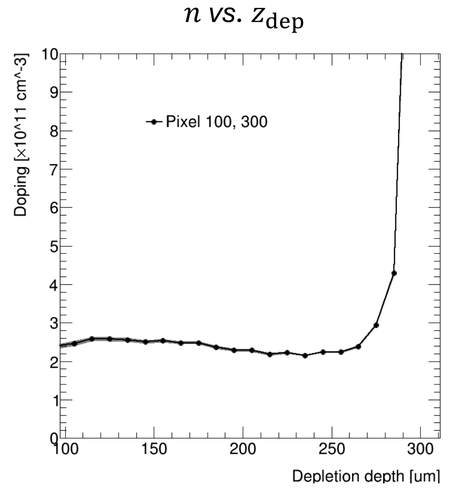
z_{dep} *vs.* V_{dep}



V_{dep} *vs.* z_{dep}^2

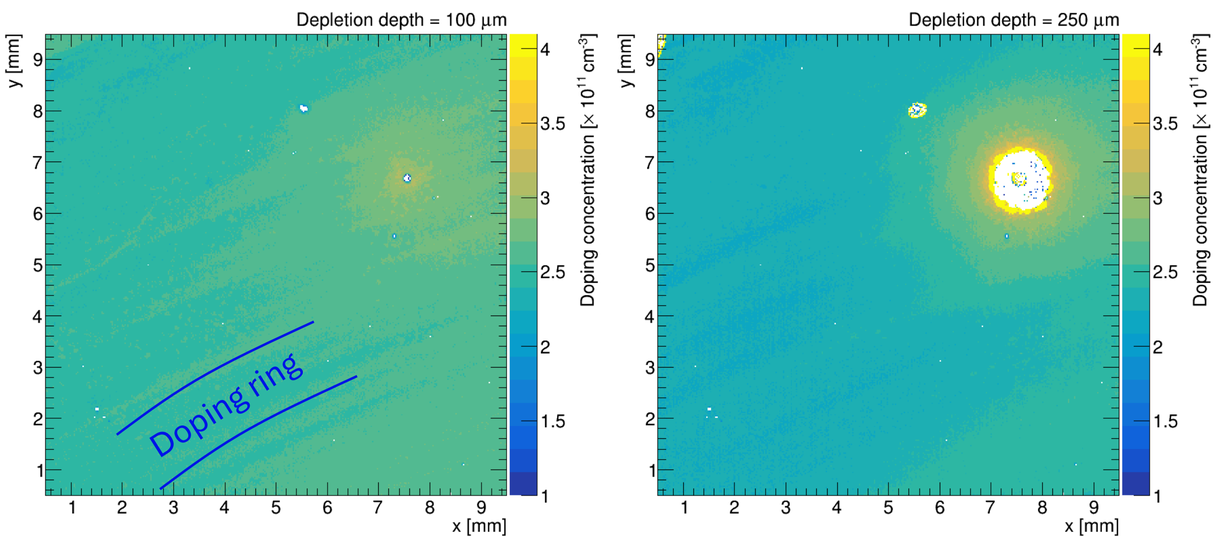


n *vs.* z_{dep}



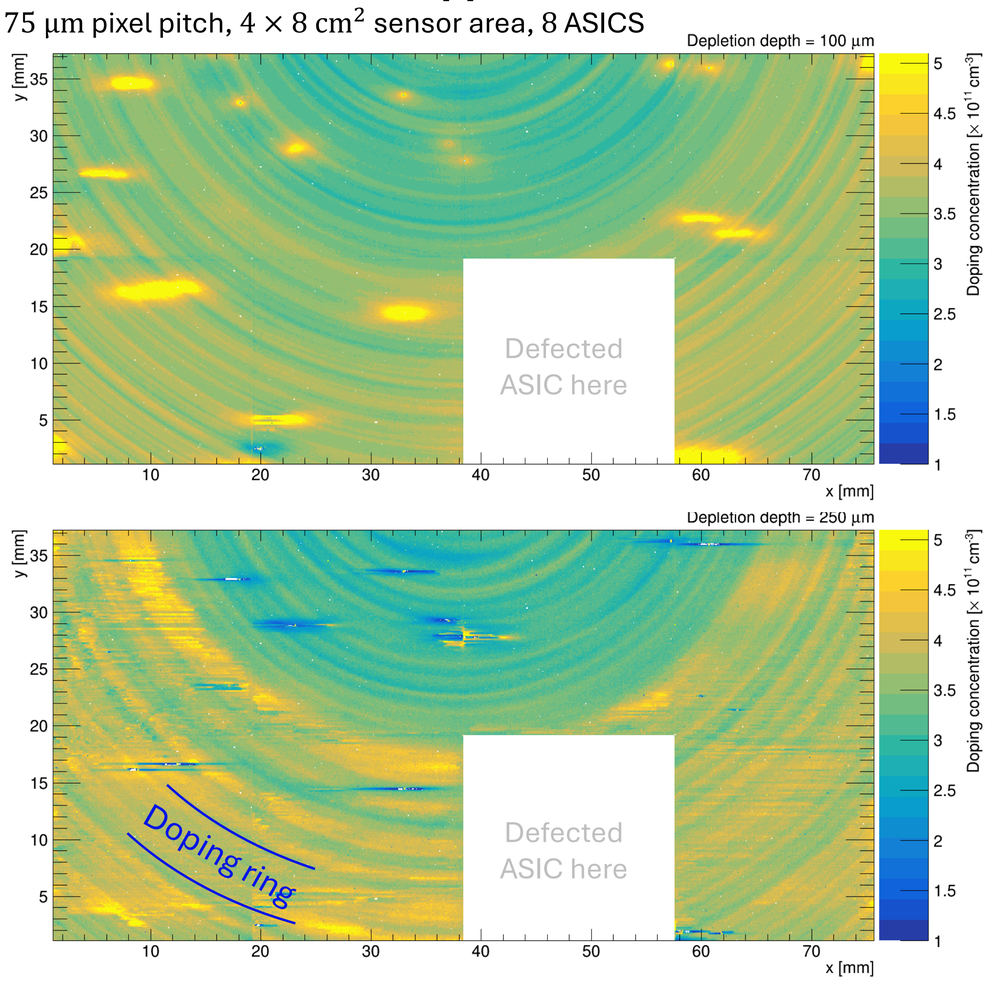
Results of Doping Profiles at Different Depths

MÖNCH detector [2]
25 µm pixel pitch, 1×1 cm^2 sensor area



- Doping non-uniformity over depth and area observed
- Doping ring structure is clearly visible in both sensors, and it develops with depth (note different sensor scales)
- Doping anomalies observed in both sensors: round/ellipse region with higher doping concentration

JUNGFRAU detector [3]
75 µm pixel pitch, 4×8 cm^2 sensor area, 8 ASICS



Conclusion

We developed a non-destructive 3D doping profiling method for silicon pixel sensors:

- Sensitive to doping concentration $> 10^{11}$ cm^{-3}
- Fine granularity down to $25 \times 25 \times 10$ µm^3 and coverage up to 4×8 cm^2
- Deliver a visualization of the doping non-uniformity after silicon sensor processing
- 3D doping can be measured with high granularity after detectors are assembled

Reference

[1] D. Mezza, et al 2016 JINST 11 C11019
[2] A. Mozzanica, et al 2018 SRN 31(6) 16-20
[3] M. Ramilli, et al 2017 JINST 12 C01071