Silicon Detectors for the Super LHC

Sally Seidel
University of New Mexico
for the RD50 Collaboration

Twelfth Vienna Conference on Instrumentation
17 February 2010

RD50

Scientific Organization of RD50

Development of Radiation Hard Semiconductor Devices for High Luminosity Colliders

CERN

Co-Spokespersons

Mara Bruzzi and ***Michael Moll***

INFN and University of Florence — CERN PH-DT

Defect / Material Characterization
Bengt Svensson
(Oslo University)

Characterization of microscopic properties of standard-, defect engineered and new materials pre- and post-irradiation

- Wodean – Workshop on Defect Analysis in Silicon Detectors (G.Lindstroem)

Defect Engineering
Eckhart Fretwurst
(Hamburg University)

Development and testing of defect engineered silicon:
- Epitaxial Silicon
- High res. CZ, MCZ
- Other impurities H, N, Ge, …
- Thermal donors
- Pre-irradiation

- Wafer procurement (M.Moll)

Pad Detector Characterization
Gregor Kramberger
(Ljubljana University)

- Test structure characterization IV, CV, CCE
- NIEL
- Device modeling
- Operational conditions
- Common irradiations
- Standardisation of measurements (A.Chilingarov)
- New Materials (E. Verbitskaya)

New Structures
Richard Bates
(Glasgow University)

- 3D detectors
- Thin detectors
- Cost effective solutions

- 3D (R.Bates)
- Semi 3D (Z.Li)
- Thinned detectors (M.Boscardin)

Full Detector Systems
Gianluigi Casse
(Liverpool University)

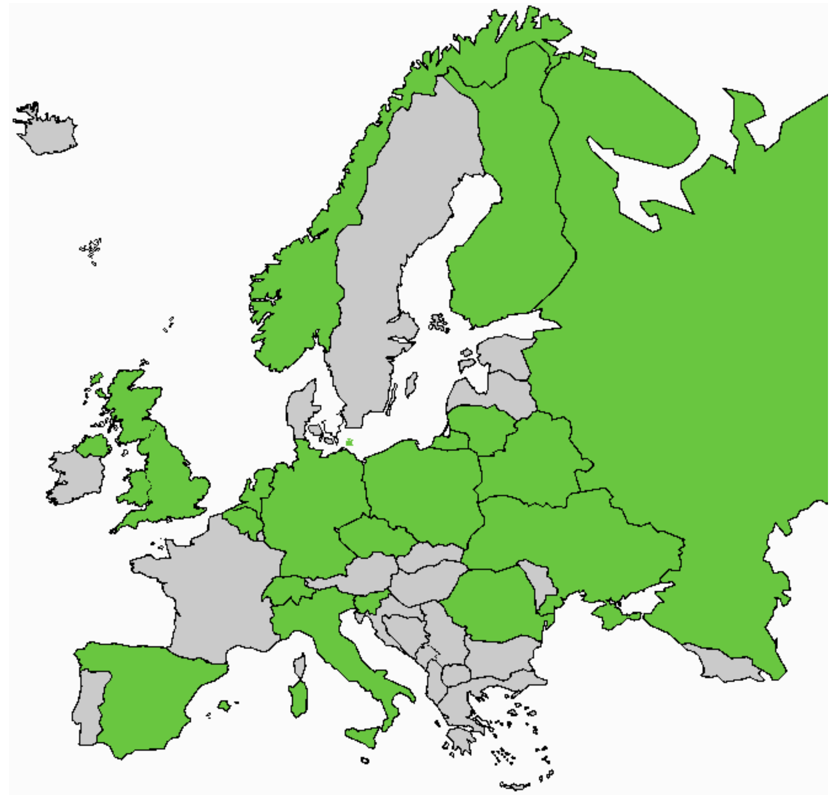
- LHC-like tests
- Links to HEP
- Links to R&D of electronics
- Comparison: pad-mini-full detectors

- Comparison of detectors made by different producers

CERN contact: Michael Moll

249 scientists and engineers from 47 member institutes:

Barcelona, Bari, BNL, Bucharest NIMP, Uni. Bucharest, CERN, Dortmund, Erfurt, Fermilab, Florence, Freiburg, Glasgow, Hamburg, Helsinki HIP, Ioffe Inst., ITE, ITME, Karlsruhe, KINR, Lancaster, Lappeenranta, Liverpool,



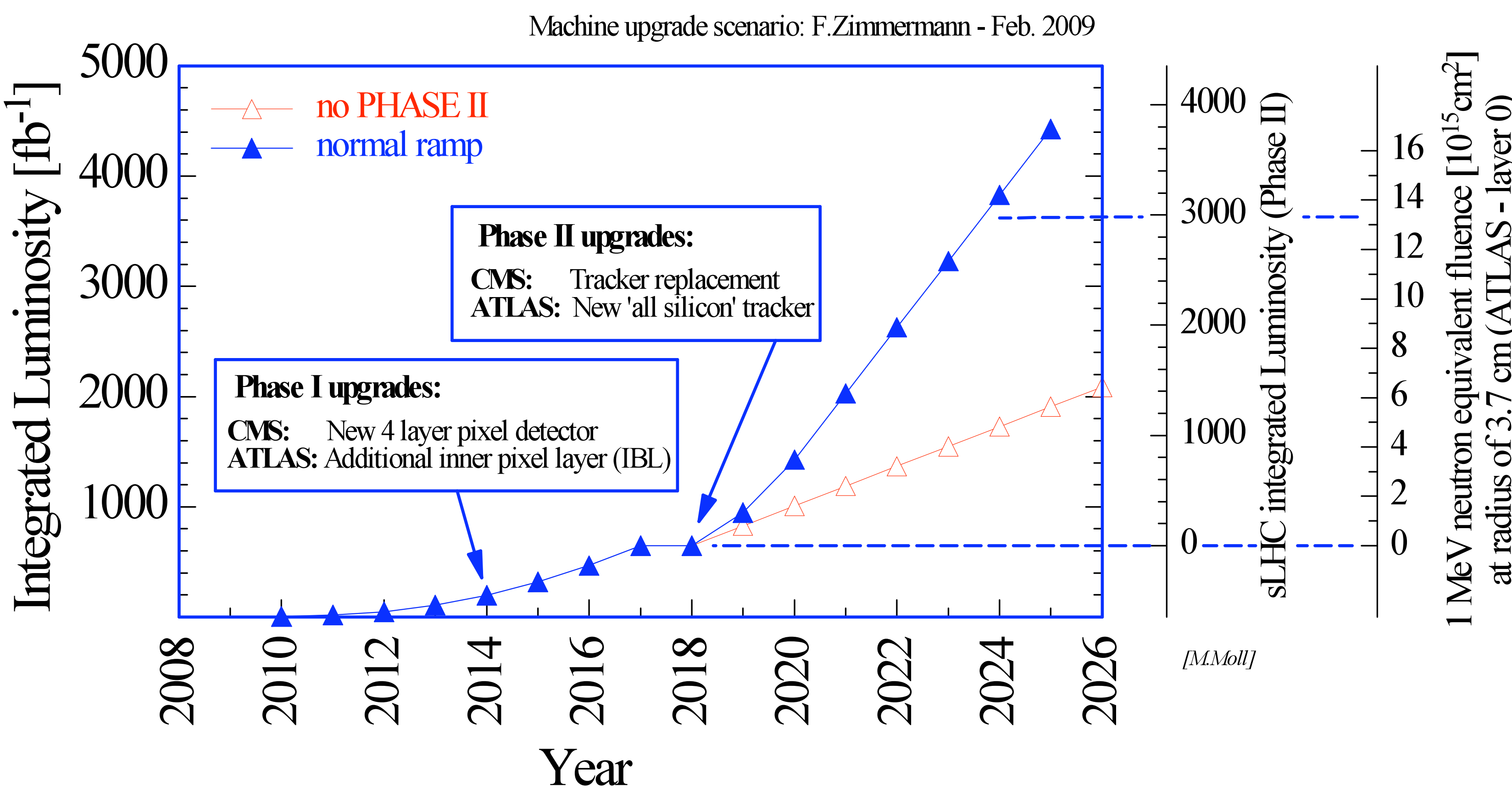
Ljubljana, Louvain, Minsk, Montreal, Moscow ITEP, Munich, New Mexico, Nikhef, Uni. Oslo, Padova, Perugia, Pisa, Prague Academy, Prague Charles, Prague CTU, PSI, Purdue, Rochester, UC Santa Cruz, SINTEF, Syracuse, Tel Aviv, Trento, Valencia, Vilnius

Super LHC (sLHC) is a proposed upgrade of the LHC to luminosity $10^{35}cm^{-2}s^{-1}$.

Expected hadron fluence at r ~ 4cm: 1.6 x 10^{16} cm^{-2} n_{eq}.

The primary limitation is trapping: decrease in charge collection efficiency.

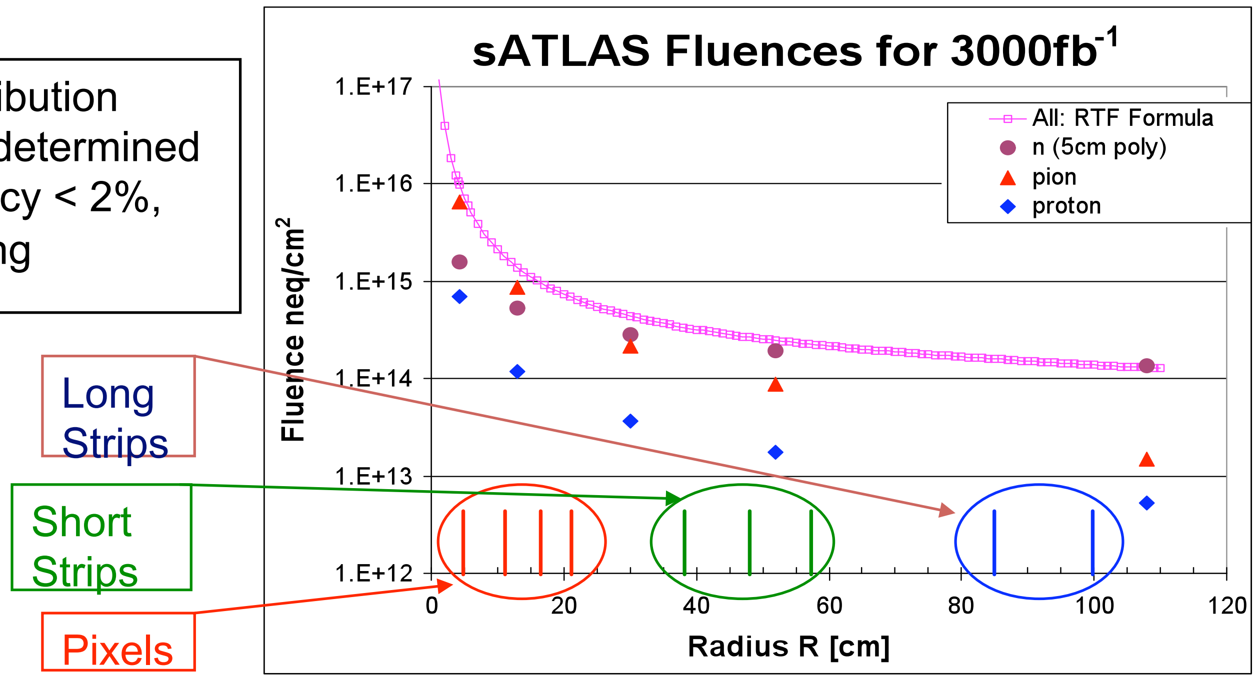
Timescale for start of sLHC under discussion, ≥ 2018.



Predicted fluences (n_{eq}), including safety factor 2:

B layer (r = 3.7 cm) 2.5 x 10^{16} (1140 MRad)
Inner pixel layer (r = 5 cm): 1.4 x 10^{16} (712 MRad)
Second pixel layer (r = 7 cm): 7.8 x 10^{16} (420 MRad)
Outer pixel layer (r = 11 cm): 3.6 x 10^{15} (207 Mrad)
Short strips (r = 38 cm): 6.8 x 10^{14} (30 Mrad)
Long strips (r = 85 cm): 3.2 x 10^{14} (8.4 Mrad)

Radial distribution of sensors determined by occupancy < 2%, still emerging



Reported here:

- Connections between microscopic defect properties and macroscopic sensor properties
- Epitaxial silicon
- Magnetic Czochralski (MCz) silicon sensors
- p-type silicon sensors
- 3D silicon sensors
- New structures

What follows is just a *sample* of recent results. For the full story, please see ***rd50.web.cern.ch/rd50/***.

Use of High Resolution Photo-induced Transient Spectroscopy to compare radiation defects in standard and oxygenated epitaxial Si

Material	[O] $[10^{16}\ cm^{-3}]$
EPI-ST 150	4.5
EPI-DO 150	14.0

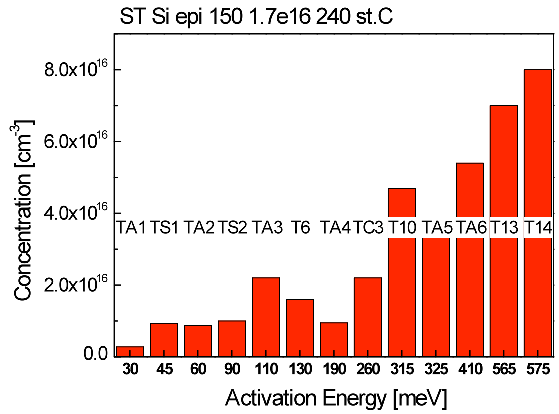
24 GeV p

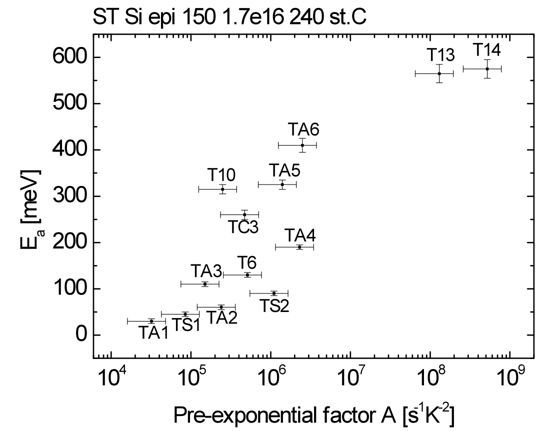
◆ *Higher [O] mainly affects shallow traps related to interstitial aggregates.*

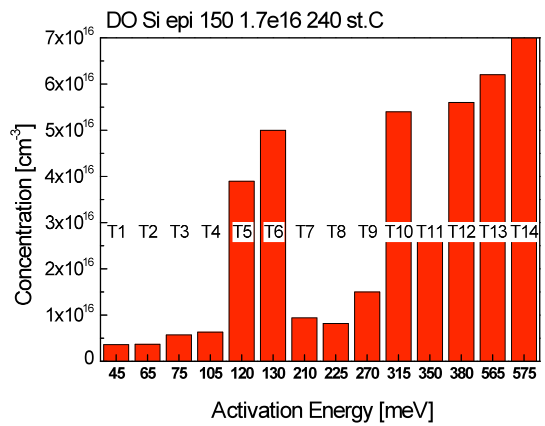
◆ *After annealing to 240°C, mid-gap traps develop independent of [O].*

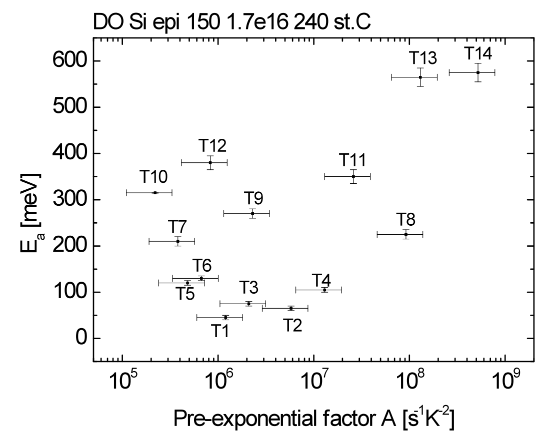
◆ *# traps is maximized in standard and oxygenated epi layers after annealing at 80 and 160 °C.*

A study of trap parameters and concentration versus oxygenation level, annealing parameters, and fluence









P. Kamiński, R. Kozłowski, J. Żelazko, M. Kozubal, E. Fretwurst

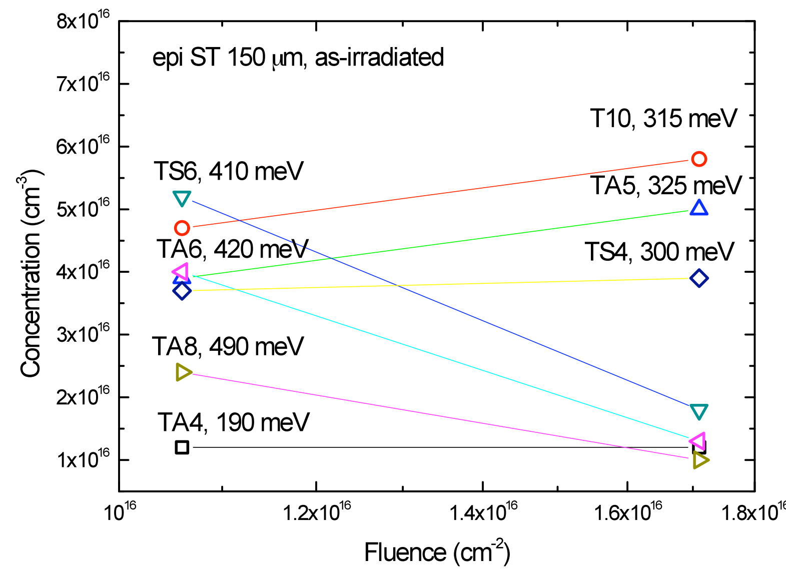
Use of High Resolution Photo-induced Transient Spectroscopy to compare radiation defects in standard and oxygenated epitaxial Si, continued

Example result, for Φ = 1.7 x 10^{16} p cm^{-2}:

Parameters of defect centers obtained from the HRPITS studies for ST Si epi 150 μm as-irradiated with proton fluence of 1.7x10^{16} cm^{-2}.

Trap label	E_a^* (meV)	A^* ($K^{-2}s^{-1}$)	Concentration (cm^{-3})	Tentative identification
TS7	20±5	1.3x10^4	1.1x10^{15}	shallow donors
TS8	30±5	3.8x10^3	3.0x10^{15}	shallow donors
TS9	90±5	4.4x10^4	6.9x10^{15}	I aggregates (I_3)
TS10	95±5	2.9x10^5	1.1x10^{16}	I aggregates (I_4) in disordered vicinity
TA4	190±10	2.3x10^6	1.2x10^{16}	VO (-/0)
T7	210±10	4.0x10^5	1.5x10^{16}	V_2 (+/0)
TS5	270±10	1.8x10^6	2.6x10^{16}	IO_2
TS4	300±10	1.5x10^6	3.9x10^{16}	V_xO_y complexes (V_3O, V_4O_2 ...)
T10	315±10	2.5x10^5	5.8x10^{16}	V_xO_y complexes (V_3O, V_4O_2 ...)
TA5	325±10	1.4x10^6	5.0x10^{16}	V_xO_y complexes (V_3O, V_4O_2 ...)
TS6	400±10	6.1x10^6	1.8x10^{16}	I_2O
TA6	410±15	2.5x10^6	1.3x10^{16}	V_2 (-/0)
TA8	480±10	1.3x10^7	1.5x10^{16}	complex of O with V aggregates (V_4, V_5)

E_a and A – the activation energy and pre-exponential factor in the Arrhenius formula $e_T = AT^2 exp(-E_a/kT)$



P. Kamiński, R. Kozłowski, J. Żelazko, E. Fretwurst

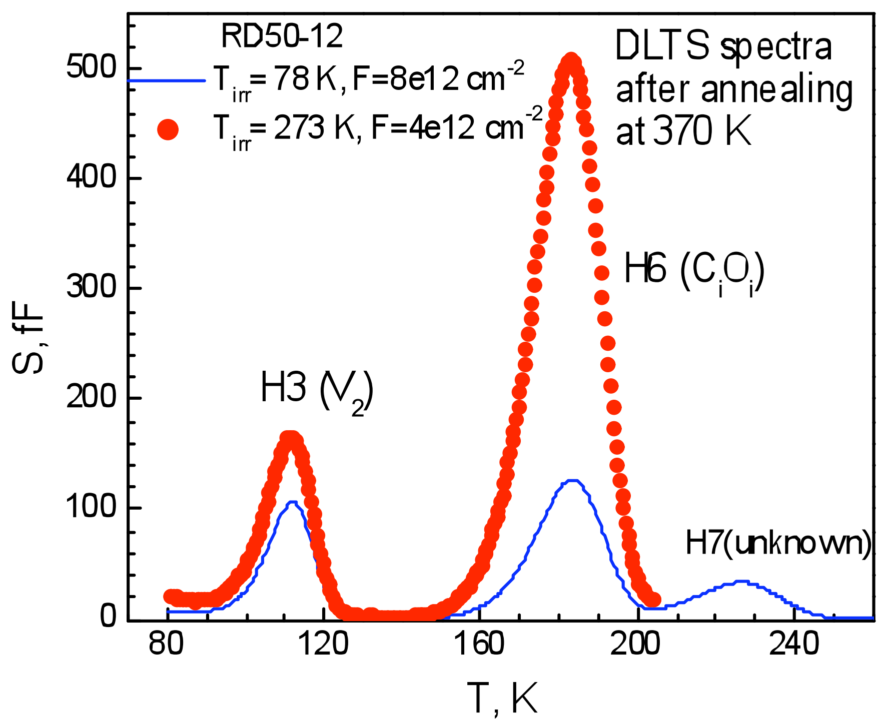
Conclusions:

- Dominant trap in low-fluence standard n-epi is at 410 meV, likely I_2O, conc. 5.2 x 10^{16} cm^{-3}. As fluence rises, 315 meV trap dominates, likely V_xO_y, conc. 5.8 x 10^{16} cm^{-3}.
- In oxygenated n-epi, 420 meV trap dominates at all fluences, likely $V_2^{-/0}$.
- After 1 hr 240°C anneal, dominant defect at 575 meV.

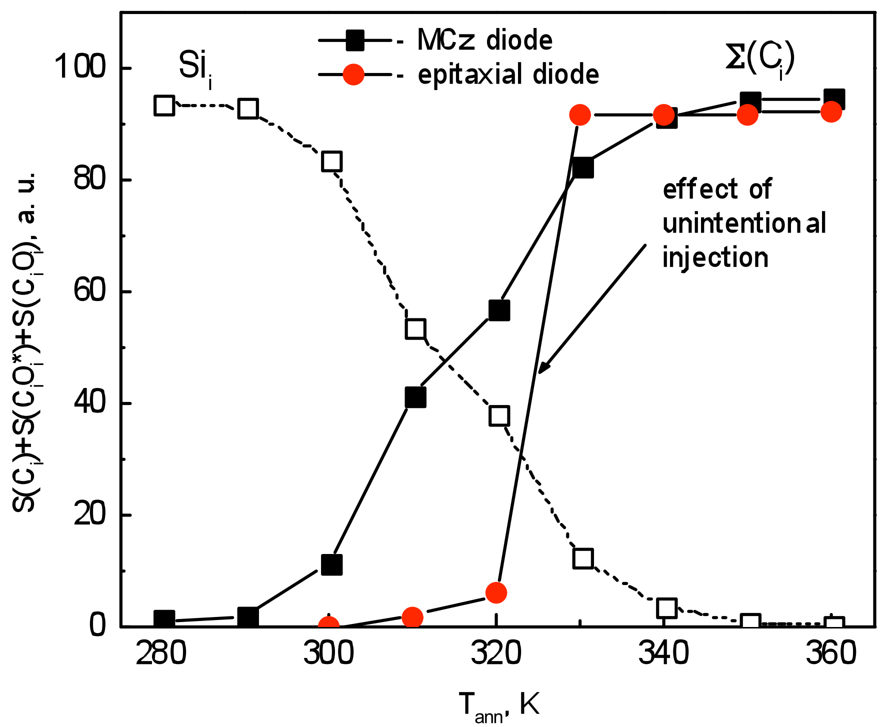
More results in defect characterization

•DLTS studies of p-Si irradiated with 6 MeV e- and α find that self-interstitial Si can persist after irradiation at 273K when (e-hole gen rate)/(Frenkel pair gen rate) is small. Mobility small at 273K. Current injection at liq Ni temperature destroys them.

L.F. Makarenko, S.B. Lastovski, L.I. Murin, M. Moll



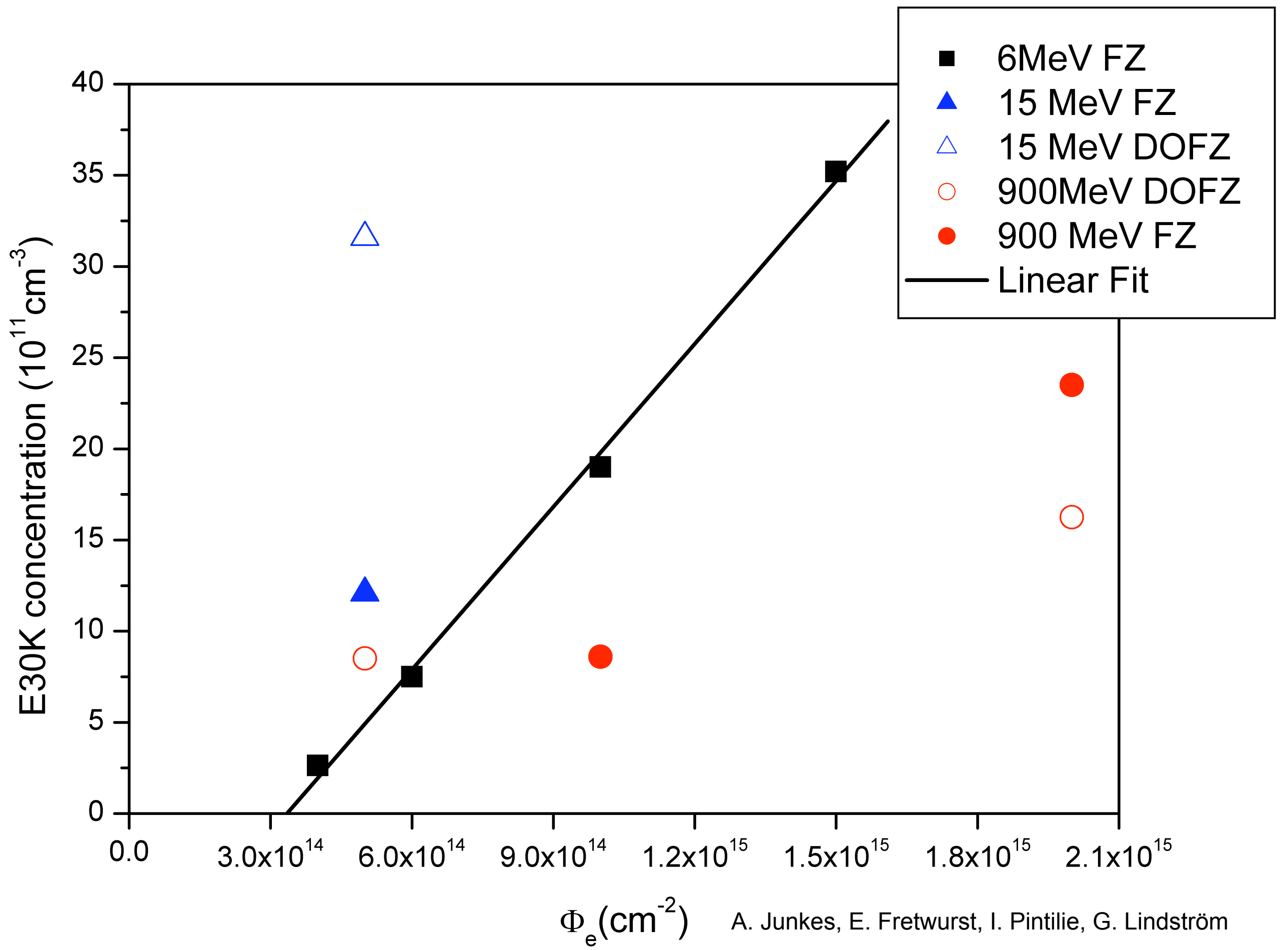
Defect introduction rate versus temp: Irradiated MCz diodes, after 30 min. annealing. Dose rate: $1x\cdot10^{11}$ cm^{-2} s^{-1}.



Growth of the concentration of C-related defects, caused by Si_i disappearance, during annealing for diodes irradiated at 78 K.

Defect characterization:

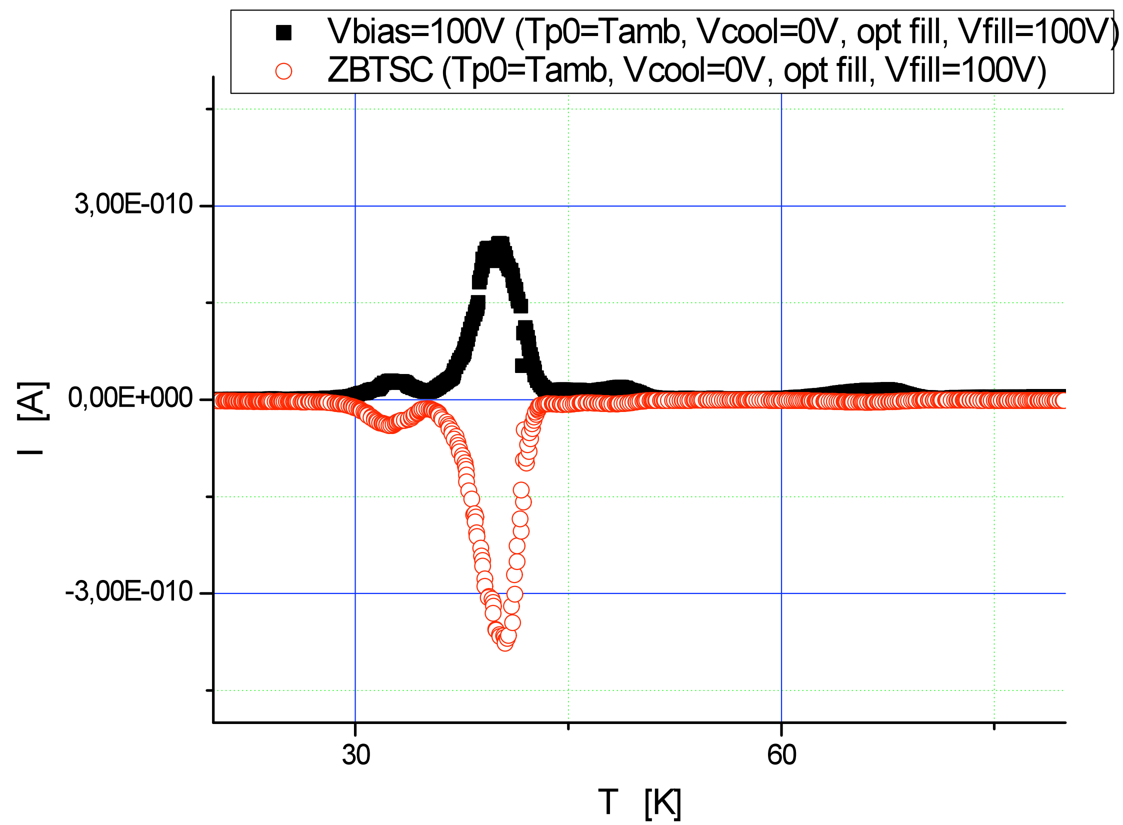
Shallow donor E(30K) generated by electron irradiation of n-type FZ diodes. E(30K), a cluster defect associated with non-type inversion of epi diodes after high p fluence, overcompensates deep acceptors. E(30K) generation is suppressed for high electron energies---suggesting point-like character?



A. Junkes, E. Fretwurst, I. Pintilie, G. Lindström

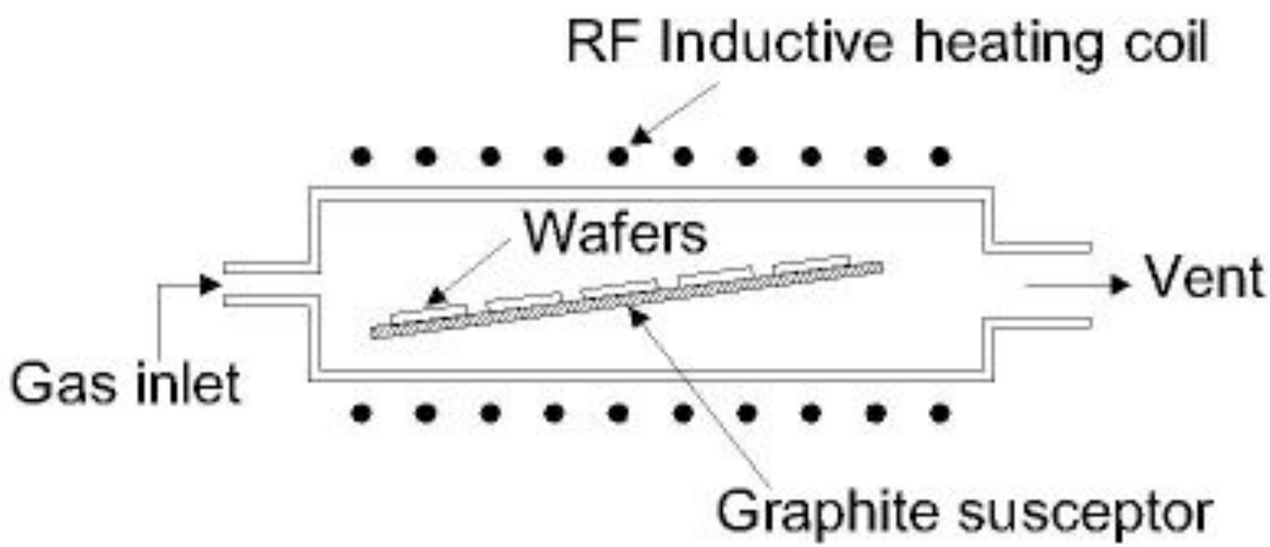
Defect characterization:

TSC study of p- and n-type MCz Si irradiated with reactor n up to 10^{16} cm^{-2}. Features correspond qualitatively to band diagrams. Interpretation: presence of residual electric field (polarization of the irradiated Si bulk) due to frozen charged traps in bulk and barriers close to electrodes. Residual field is opposed to external V_{bias}.

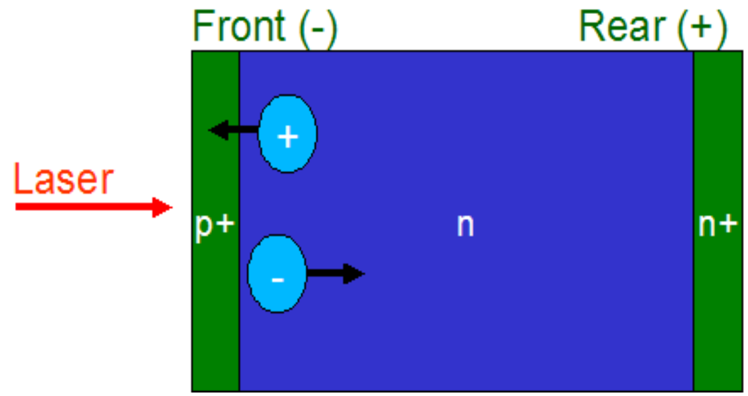


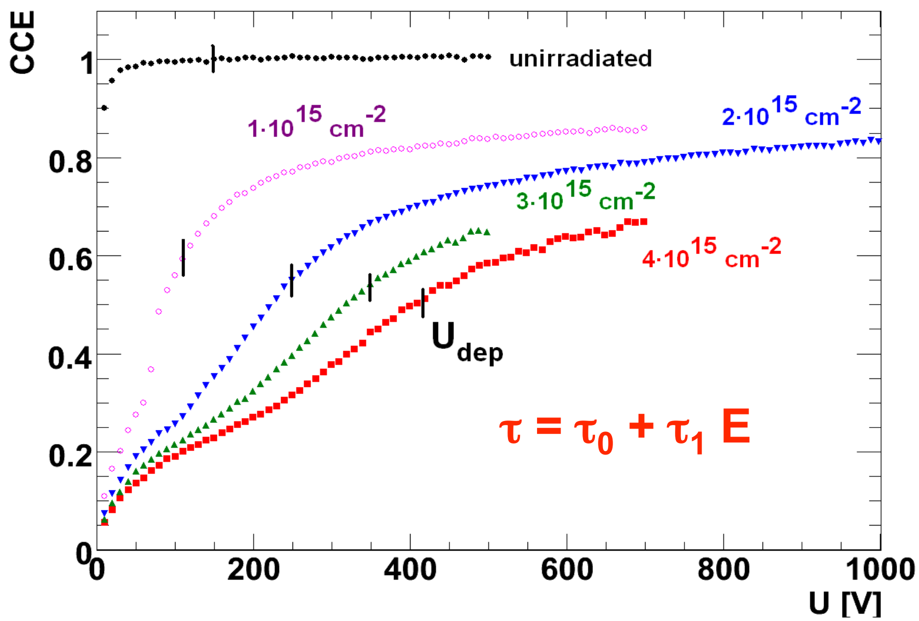
Epitaxial silicon

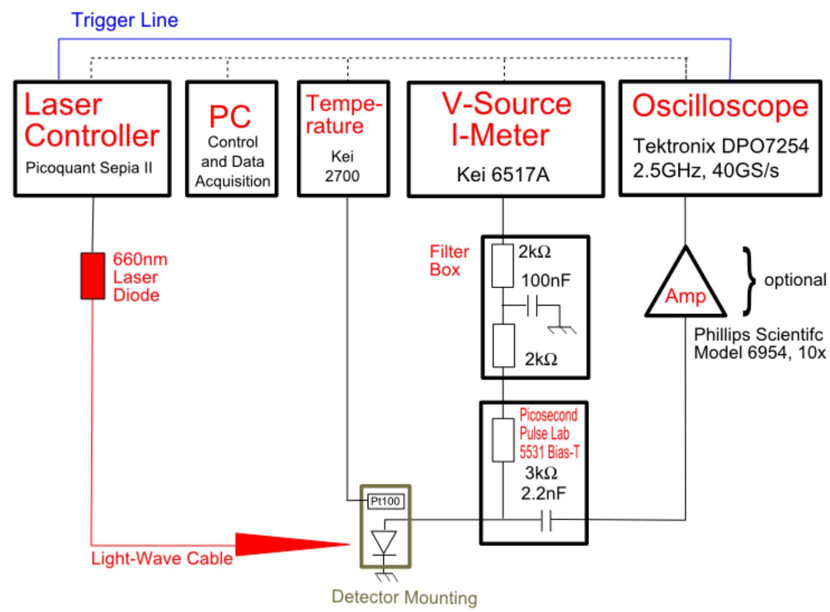
Benefits: oxygenation and controlled thin layer growth



TCT studies and simulation of charge collection in 150µm-thick epi devices after ϕ=(1 - 4) x 10^{15} cm^{-2} reveal field-dependent contribution to lifetimes.







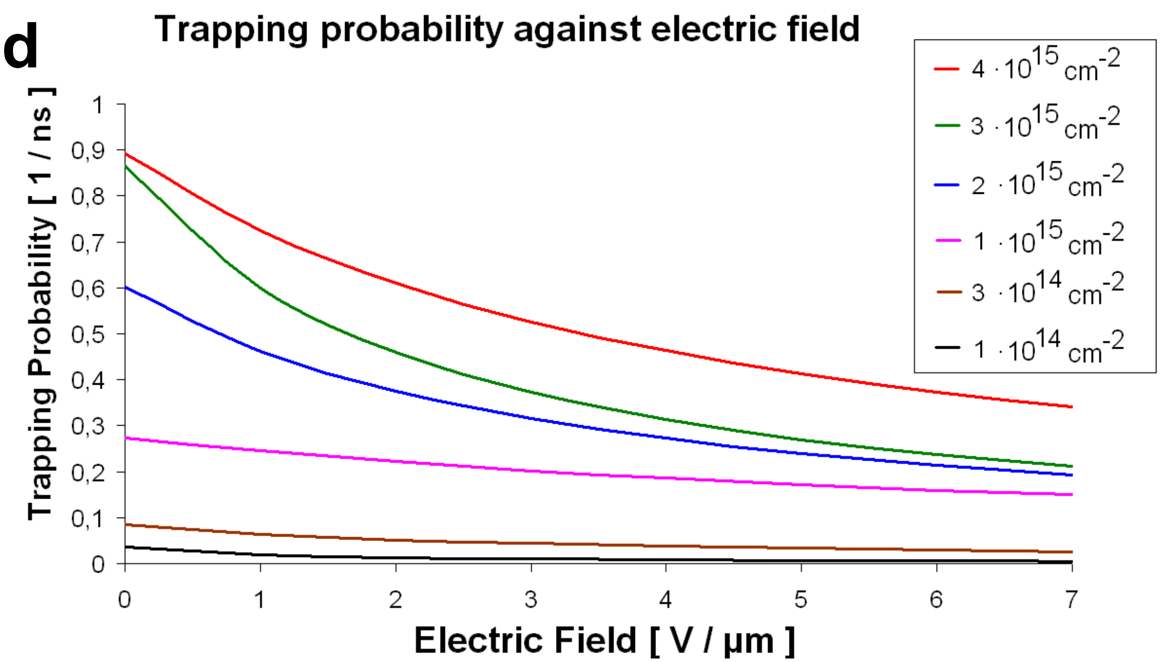
$$-\,dN = \frac{1}{\tau\,(E(x(t)))}\;N\,dt$$

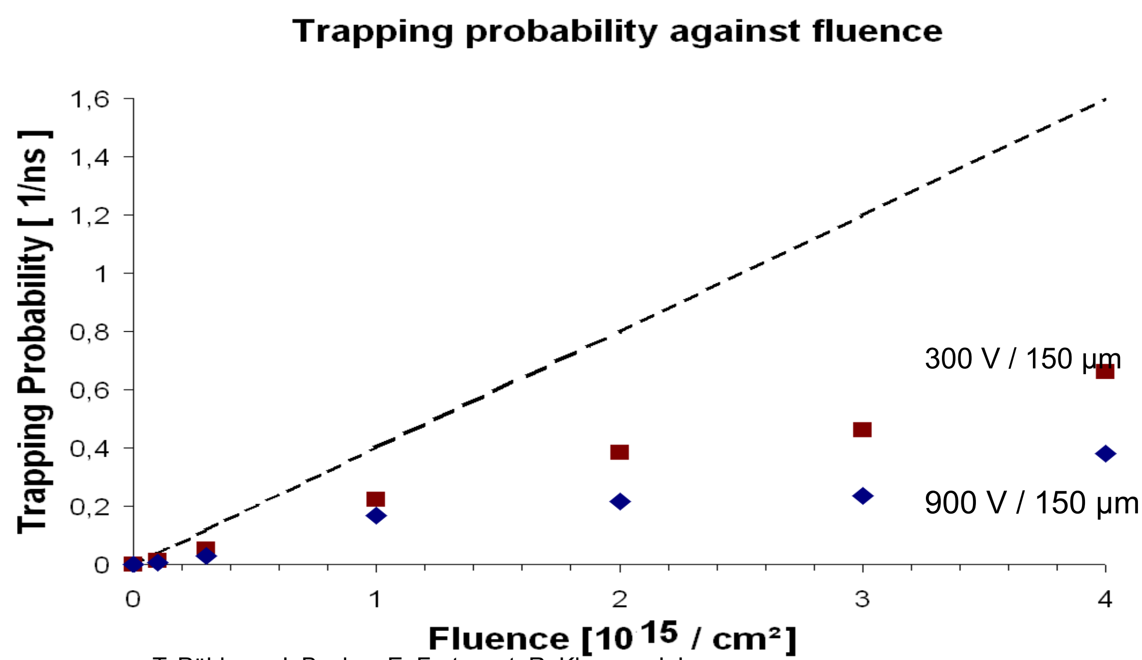
T. Pöhlsen, J. Becker, E. Fretwurst, R. Klanner, J. Lange

Epitaxial Si, continued

Charge collection, trapping well described by including:

- distortions to the space charge distribution leading to parabolic electric fields (double peak)
- field-dependence of trapping time τ (to fit CCE curves)
- electronic circuit effects (to simulate TCT signals)
- Trapping probability decreases with increasing E-field: *high E-fields desirable* to reduce trapping probability



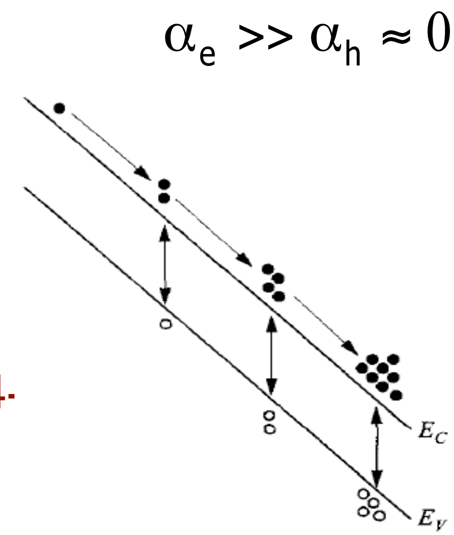


T. Pöhlsen, J. Becker, E. Fretwurst, R. Klanner, J. Lange

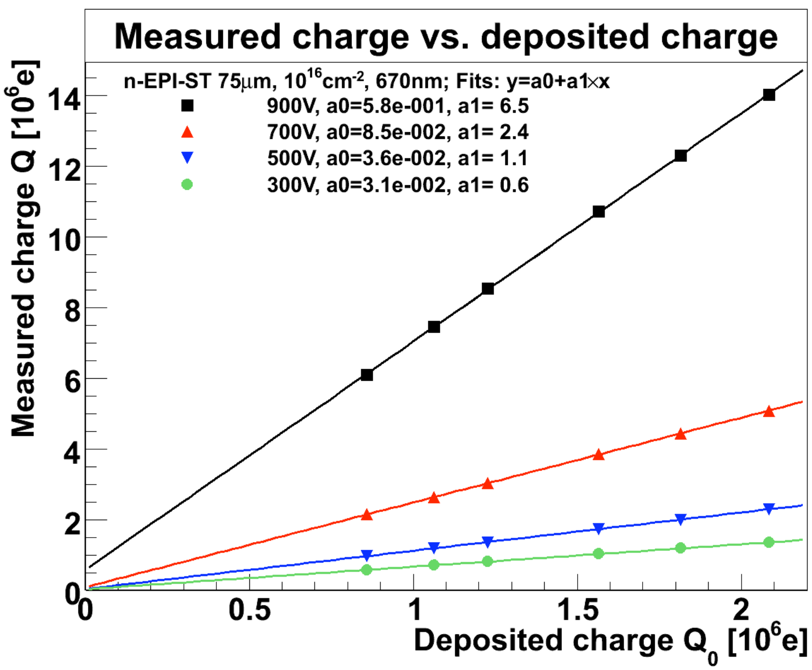
Studies of charge multiplication in highly irradiated sensors

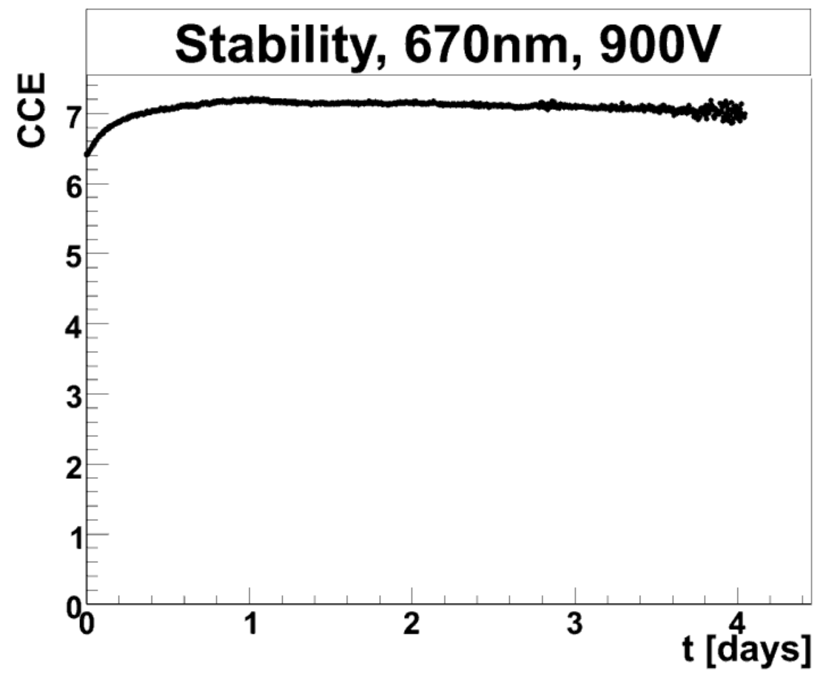
Please see talk by Lange, Junkes, et al.

n-type epitaxial, [O] = 9x10^{16}cm^{-3}, <111>, $N_{eff,0}$=2.6x10^{13}cm^{-3}



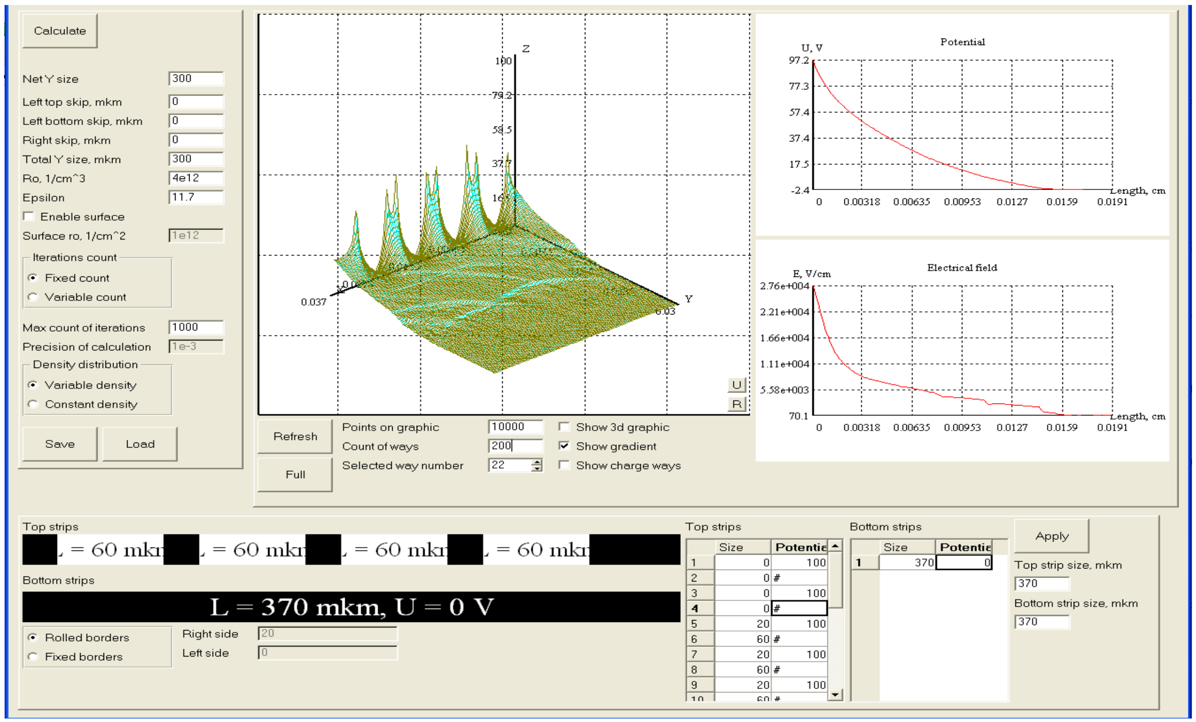
Beneficial Charge Multiplication in highly irradiated (10^{16}cm^{-2} 24-GeV p) devices due to impact ionization provides proportional response, long-term stability, homogeneous production, only slight noise increase.





J. Lang, J. Becker, E. Fretwurst, R. Klanner, G. Lindström

A theoretical model for charge multiplication



- Assume avalanche multiplication in p-n junctions and E field controlled by current injection in deep-level doped semiconductors.
- Model has only 2 free parameters, uses E field in detector base region and potential sharing between base and depleted region adjacent to segmented side.

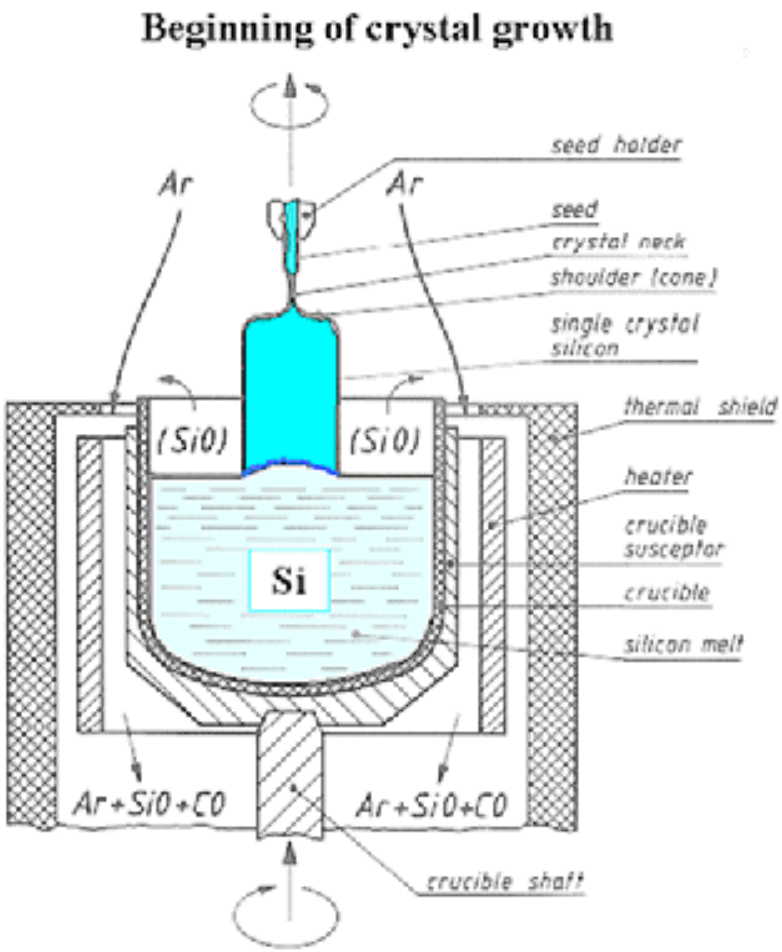
•Predicts: charge multiplication can only occur in detectors with segmented n+ side.

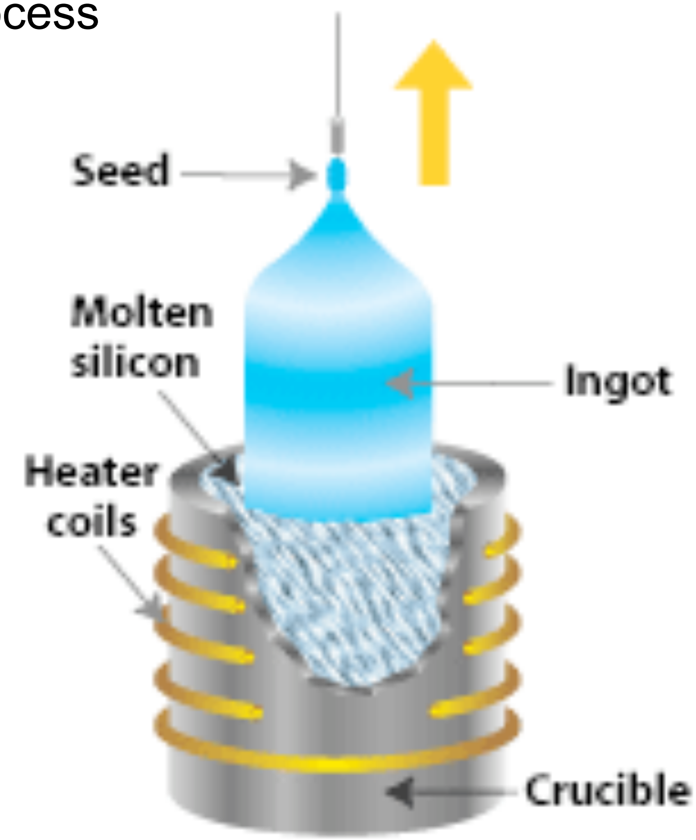
V. Eremin, E. Berbitskaya, Z. Li, J. Härkönen

Czochralski silicon

Please see also the talk by L. Spiegel

Benefit: enhanced oxygenation intrinsic to the process





Czochralski studies of charge collection versus fluence

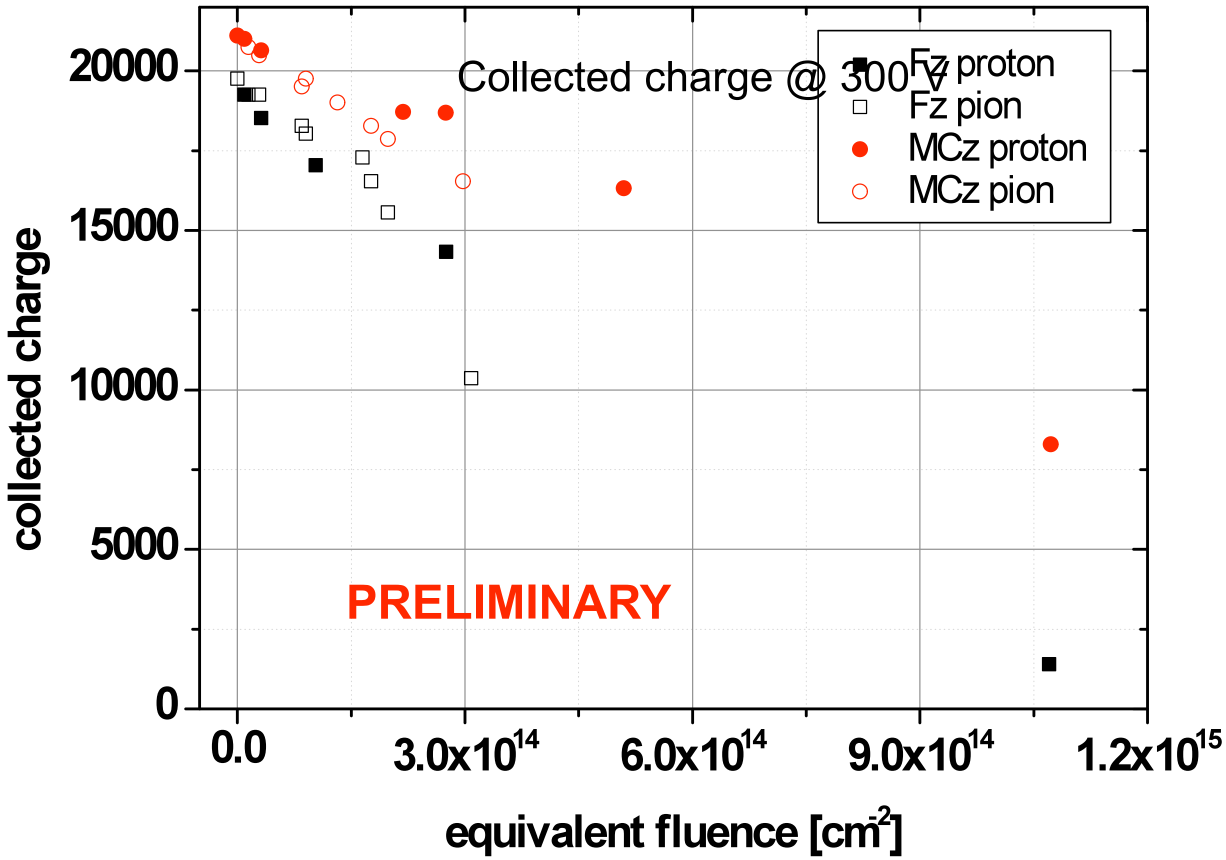
- Comparison of V_{dep} and I_{leak} in n-Fz and n-MCz after (24 GeV) proton and (300 MeV) pion irradiation

- MCz: 1 kΩ-cm (V_{dep} 300V); FZ: 15 kΩ-cm (V_{dep} 20V)

- Collected charge on MCz > on FZ

- Collected charge less after pion than after proton irradiation

- Conclusions: trapping probability lower after pion irradiation; hole trapping different for FZ and MCz.

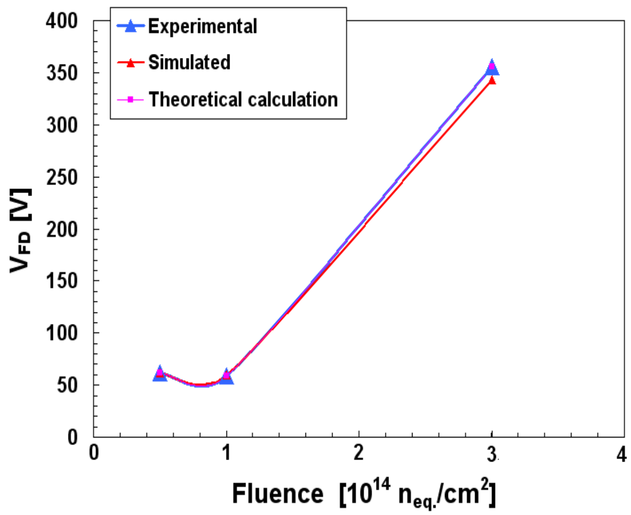


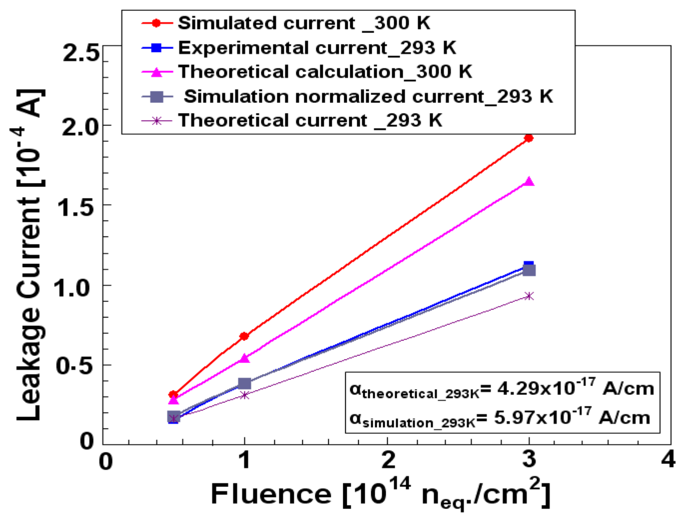
K. Kaska, M. Fahrer, M. Moll

Device modeling of neutron damage effects in n-MCz Si

Parameters of the 'four trap level model' for n-type MCz Si

trap type	energy level [eV]	$\sigma_{n,p}$ [cm²] from exp.	σ_n [cm²]	σ_p [cm²]	η [cm^{-1}]
$E_5^{(-/0)}$	E_c-0.46	1.0 x 10^{-14}, 1.0 x 10^{-13} (estimated)	3.0 x 10^{-15}	4.1 x10^{-13}	12.4
H152 K $^{(0/-)}$	E_v+0.42	unknown, 2.3x10^{-14}	3.05 x 10^{-13}	1.0 x 10^{-13}	0.06
$C_iO_i^{(+/0)}$	E_v+0.36	2.05 x 10^{-18}, 1.64 x 10^{-14}	1.64 x 10^{-14}	2.24 x 10^{-14}	1.1
E30K$^{(0/+)}$	E_c-0.1	2.3x10^{-14}, 2.7 x 10^{-15}	2.77 x 10^{-15}	2.0 x 10^{-15}	0.017





A. K. Srivastava, D. Eckstein, E. Fretwurst, R. Klanner, G. Steinbrück

- Good agreement in $V_{full\ dep}$ and I_{leak} between simulation (Synopsys TCAD) and data.
- Theoretical calculations based on Shockley Read Hall recombination theory reproduce the $V_{full\ dep}$ data but underestimate the measured I_{leak} at 293K.
- Plan: mixed irradiation model (n-MCz Si) for charge carrier trapping, electric field distribution.

Low resistivity n-Czochralski:

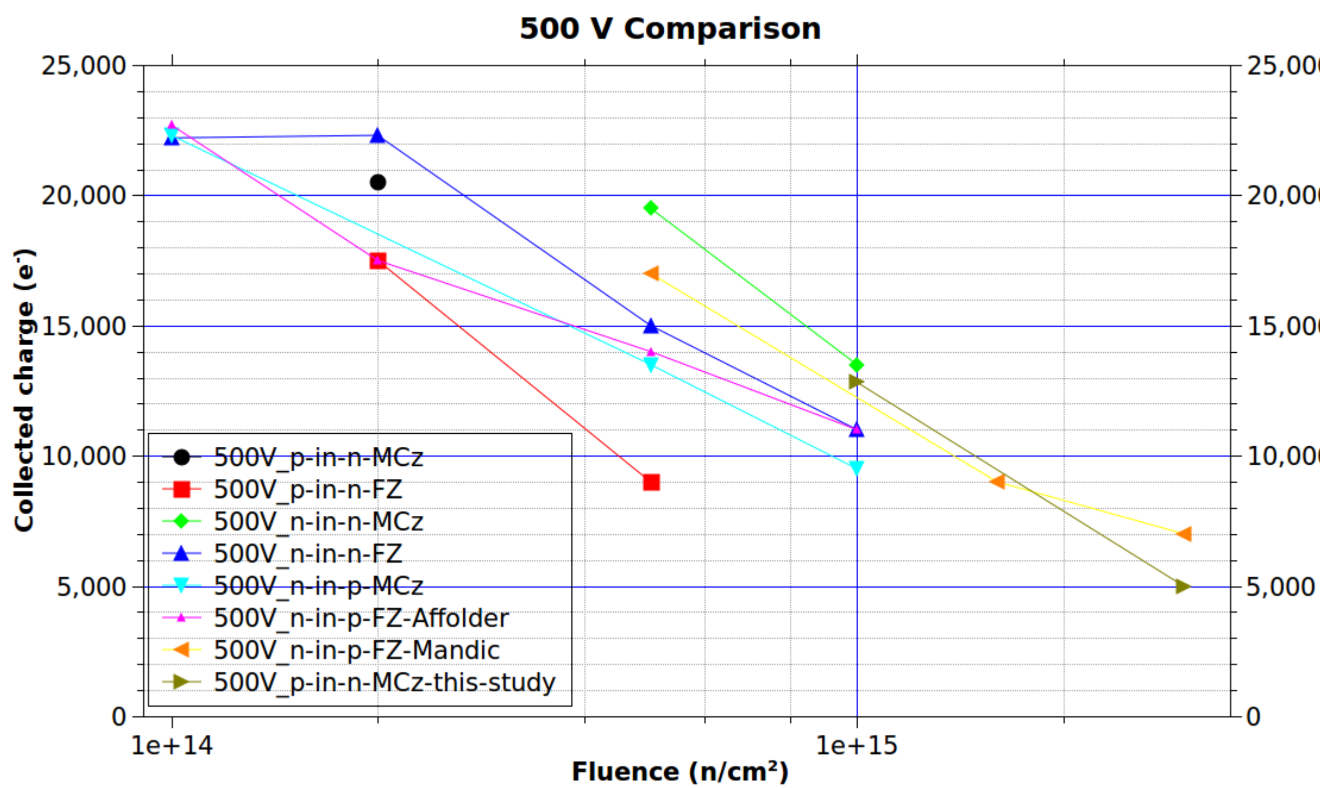
•Motivated by challenges to strip isolation in p-type.

•Competitive with p-FZ up to few x 10^{15} n.

•Good CCE up to 10000 min @ 60°C.

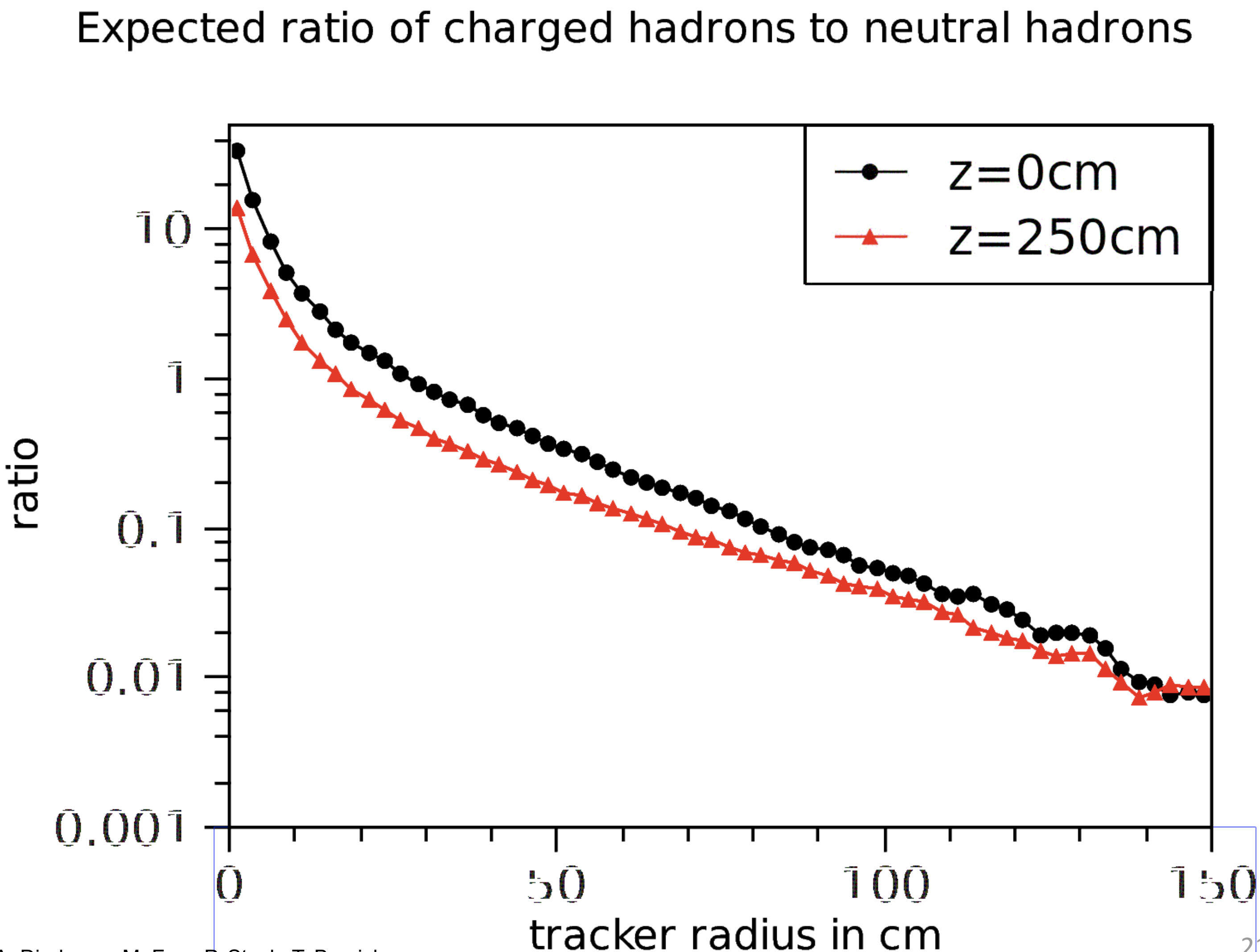
•The challenge: high current.

N. Pacifico, E. del Castillo Sanchez, M. Fahrer, M. Moll



Mixed irradiation of sensors in Czochralski silicon

Irradiated with neutron-proton mix with charged/neutral as expected at sLHC



R. Eber, Th. Müller, W. de Boer, A. Dierlamm, M. Frey, P. Steck, T. Barvich

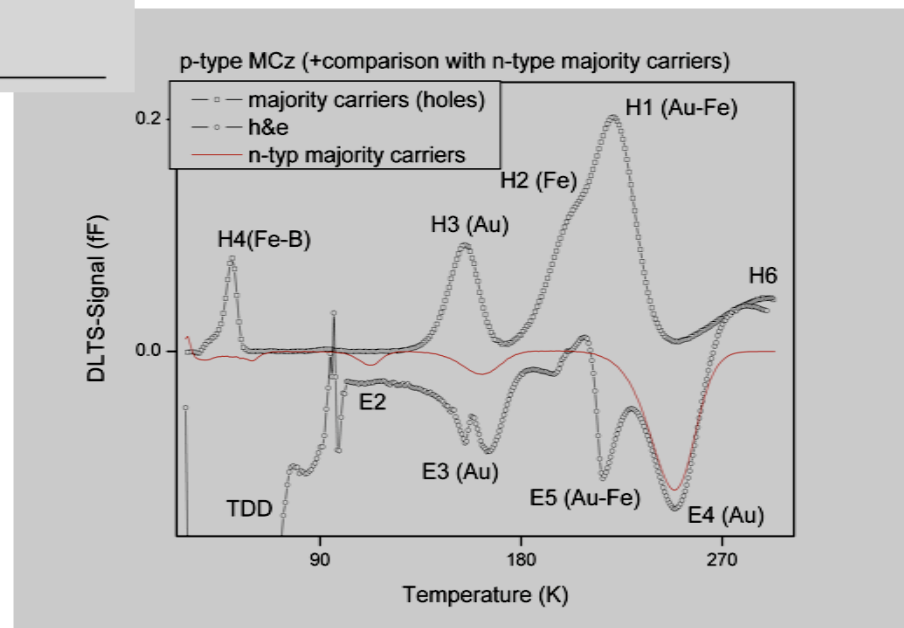
Mixed irradiation of sensors in Czochralski silicon, continued

Trapping times extracted for fluences < 10^{15} cm^{-2} n_{eq}

Diode	$F_{eq}(n)$ $\left[\frac{n_{eq}}{cm^2}\right]$	$F_{eq}(p)$ $\left[\frac{n_{eq}}{cm^2}\right]$	τ_e[ns]	τ_h[ns]	β'_e $\left[\frac{cm^2}{ns}\right]$	β'_h $\left[\frac{cm^2}{ns}\right]$
MCz-n_3N-A	$3,2 \cdot 10^{14}$	-	$5,96 \pm 0,7$	$2,87 \pm 0,8$	$5,2 \cdot 10^{-16}$	$10,8 \cdot 10^{-16}$
MCz-n_3N-B	$3,5 \cdot 10^{14}$	-	$5,40 \pm 0,6$	$1,21 \pm 1,0$	$5,3 \cdot 10^{-16}$	$23,6 \cdot 10^{-16}$
MCz-n_4-A	$3,3 \cdot 10^{14}$	$6,8 \cdot 10^{13}$	$4,92 \pm 0,5$	$2,2 \pm 0,5$	$5,2 \cdot 10^{-16}$	$11,6 \cdot 10^{-16}$
MCz-n_4-B	$3,0 \cdot 10^{14}$	$6,8 \cdot 10^{13}$	$4,44 \pm 0,5$	$1,51 \pm 0,6$	$6,1 \cdot 10^{-16}$	$17,9 \cdot 10^{-16}$
MCz-n_6-A	$3,6 \cdot 10^{14}$	$2,9 \cdot 10^{14}$	$3,00 \pm 1,5$	$1,74 \pm 2,0$	$5,1 \cdot 10^{-16}$	$8,84 \cdot 10^{-16}$
MCz-n_17-A	$4,4 \cdot 10^{14}$	$1,3 \cdot 10^{15}$				
MCz-n_108-A	$8,1 \cdot 10^{14}$	$1,0 \cdot 10^{16}$				

Diode	$F_{eq}(n)$ $\left[\frac{n_{eq}}{cm^2}\right]$	$F_{eq}(p)$ $\left[\frac{n_{eq}}{cm^2}\right]$	τ_e[ns]	τ_h[ns]	β'_e $\left[\frac{cm^2}{ns}\right]$	β'_h $\left[\frac{cm^2}{ns}\right]$
MCz-p_3N_spray	$3,2 \cdot 10^{14}$	-	$6,7 \pm 2,6$	$1,8 \pm 1,9$	$4,7 \cdot 10^{-16}$	$17,4 \cdot 10^{-16}$
MCz-p_4_spray	$3,1 \cdot 10^{14}$	$6,8 \cdot 10^{13}$	$5,3 \pm 4,9$	$5,7 \pm 4,0$	$5,1 \cdot 10^{-16}$	$4,7 \cdot 10^{-16}$
MCz-p_6_spray	$3,7 \cdot 10^{14}$	$2,9 \cdot 10^{14}$	$2,3 \pm 1,2$	$2,2 \pm 2,2$	$6,6 \cdot 10^{-16}$	$6,9 \cdot 10^{-16}$
MCz-p_17_stop	$4,5 \cdot 10^{14}$	$1,3 \cdot 10^{15}$	-	-		
MCz-p_108_stop	$7,4 \cdot 10^{14}$	$1,0 \cdot 10^{16}$	-	-		

R. Eber, Th. Müller, W. de Boer, A. Dierlamm, M. Frey, P. Steck, T. Barvich

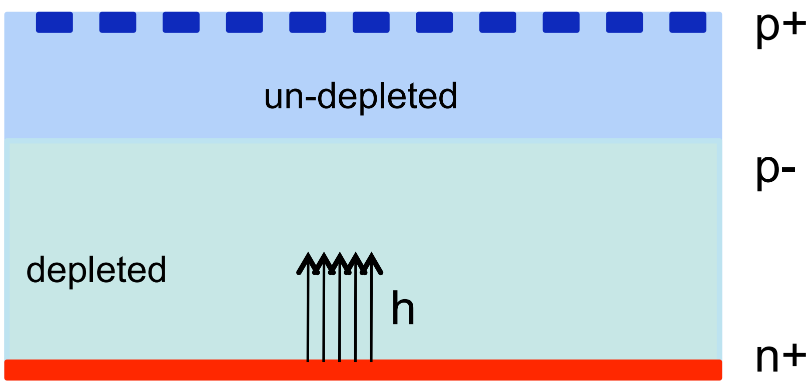


Defect sources....gold?

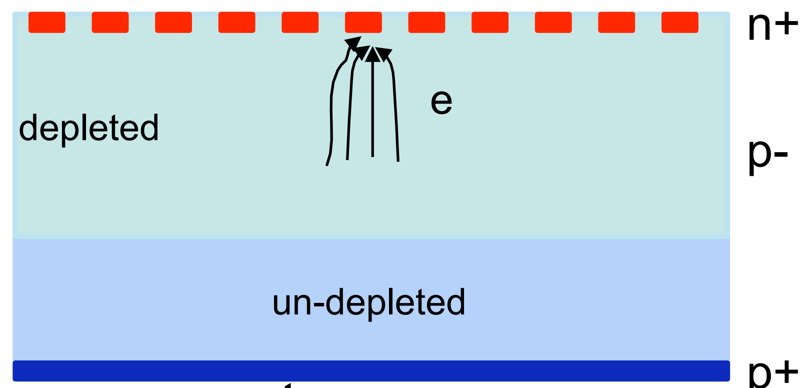
Sensors in p-type bulk

Benefits:

- collect electrons
- no radiation-induced type inversion
- single-sided processing reduces cost

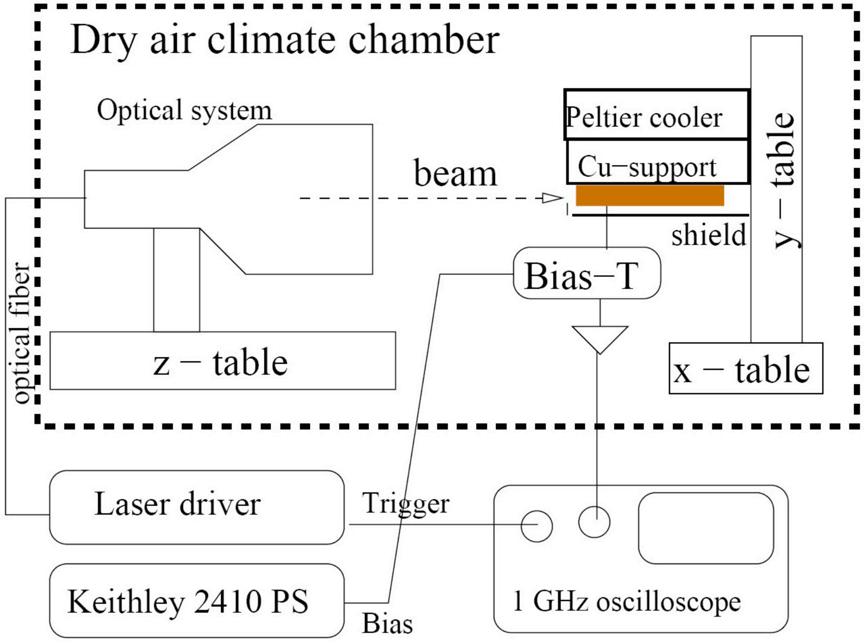


p-on-n geometry (after type inversion)

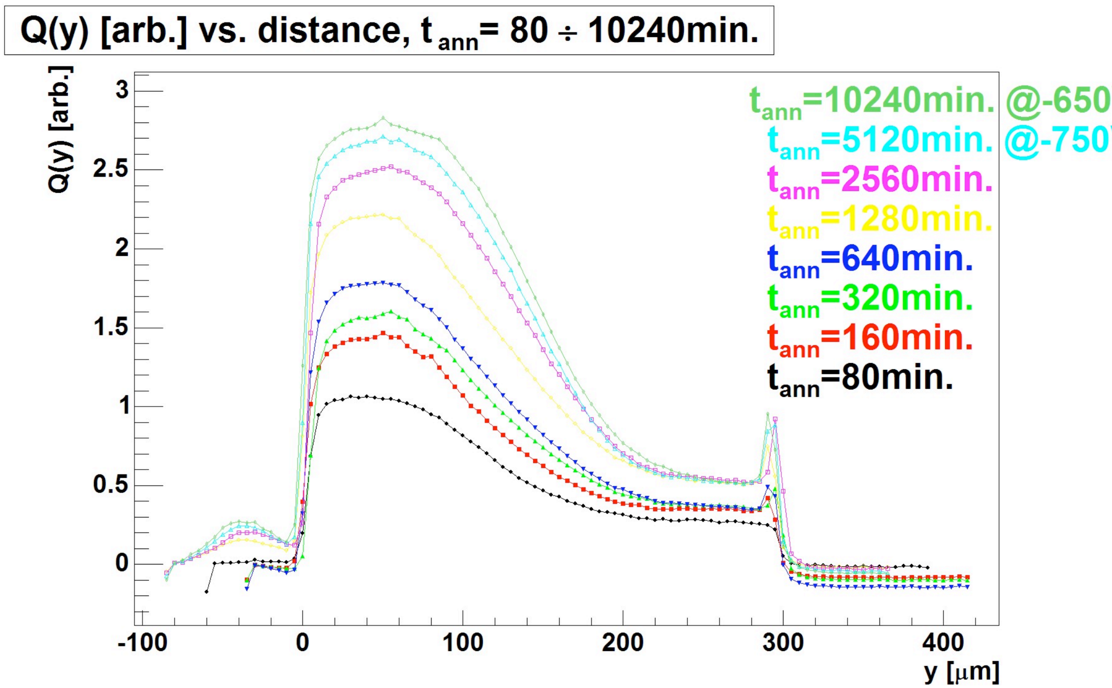


n-on-p geometry
n-on-n geometry (after type inversion)

Edge-TCT study of long term annealing on highly irradiated Si detectors



- p-FZ Si received 5x10^{15} n
- Sample annealed in the setup with the Peltier.
- Charge measurement precision: a few percent.
- Laboratory temperature: 21 ^{o}C.



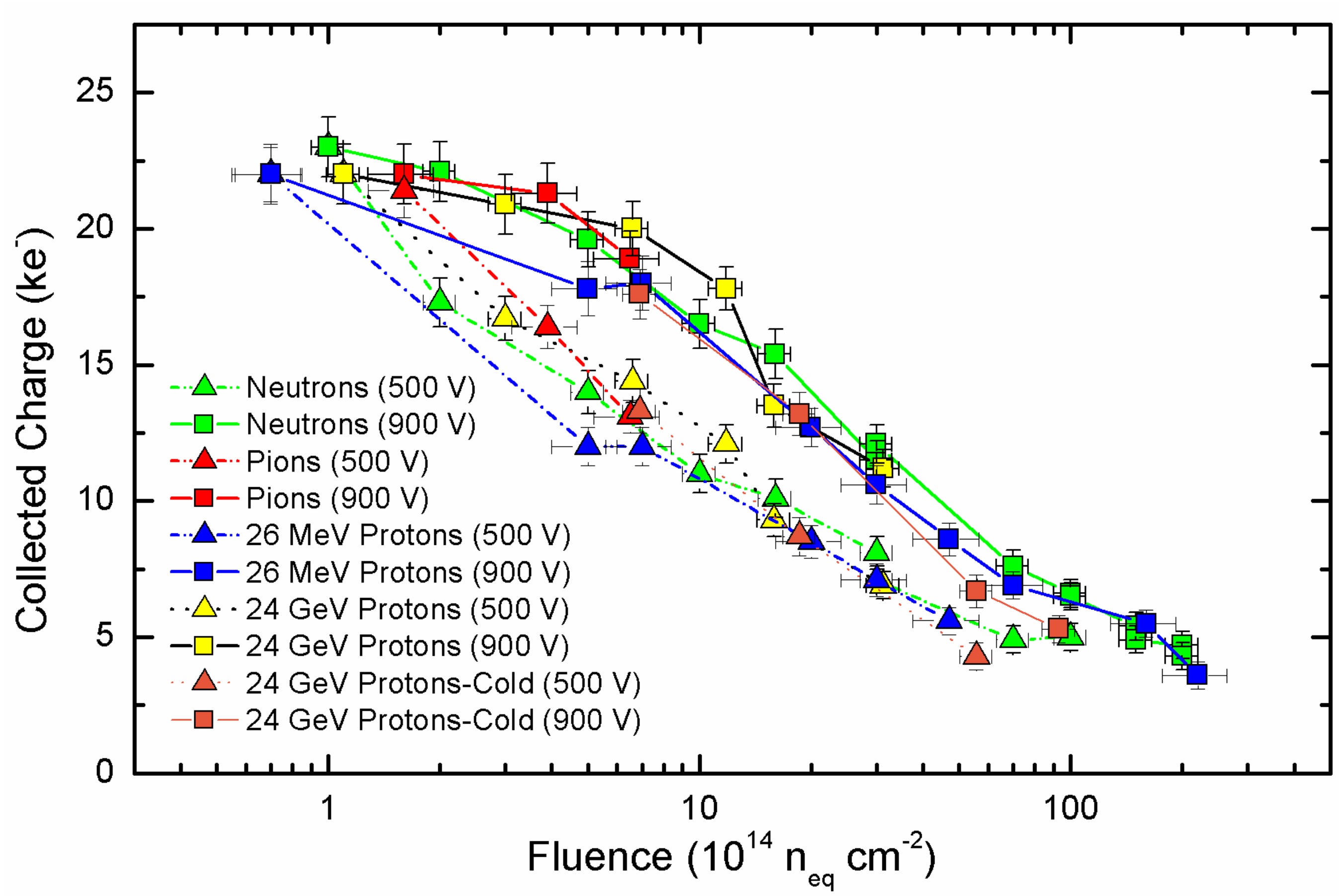
- The same locations in the detector were illuminated for all annealing steps.
- Sample temperature stabilized to less than 1°C.
- Annealing at 60°C.
- After each annealing step, voltage scans from -800V to 500V.

G. Kramberger, V. Cindro, I. Mandić, M. Mikuž, M. Milovanović, M. Zavrtanik

Charge collection efficiencies of *n-in-p* planar sensors after n, p, and π irradiation

Corrected for annealing for pions and 24 GeV p

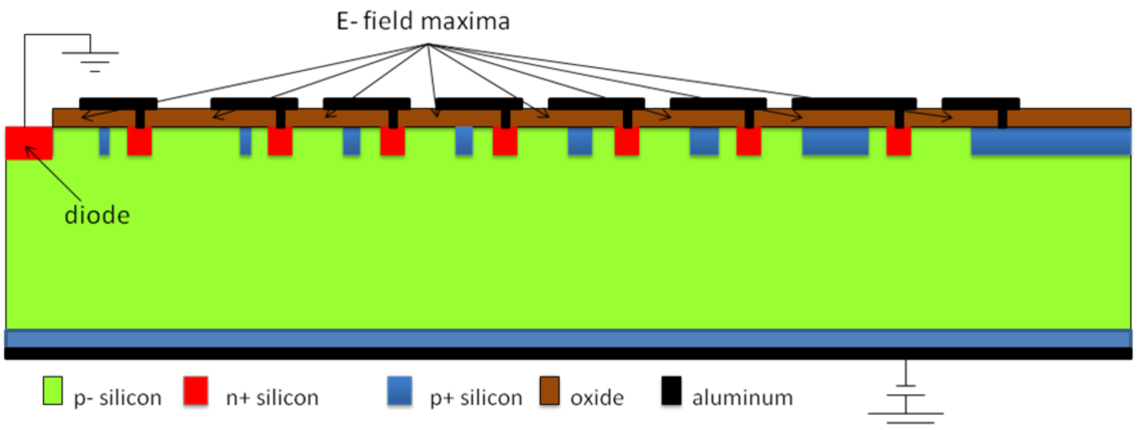
Charge collected by n-in-p FZ Si may be sufficient at innermost layer.

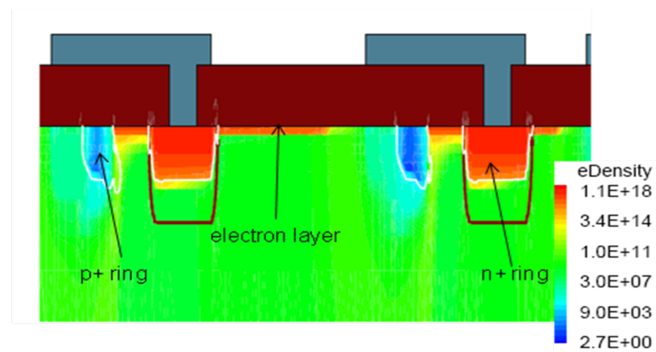


A. Affolder, G. Casse, P. Allport

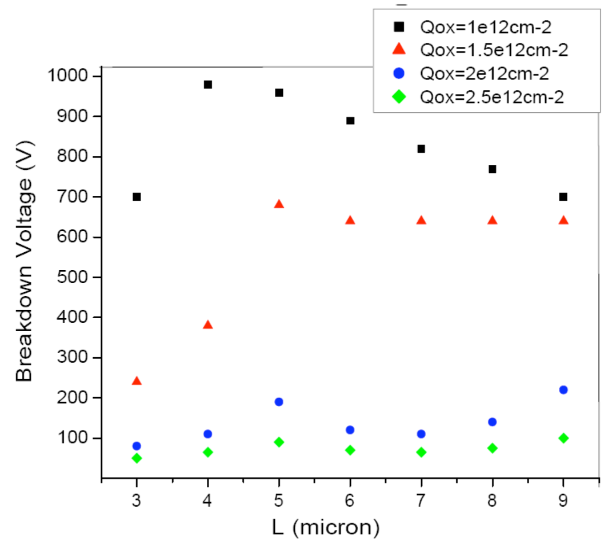
Guard ring design for n-on-p

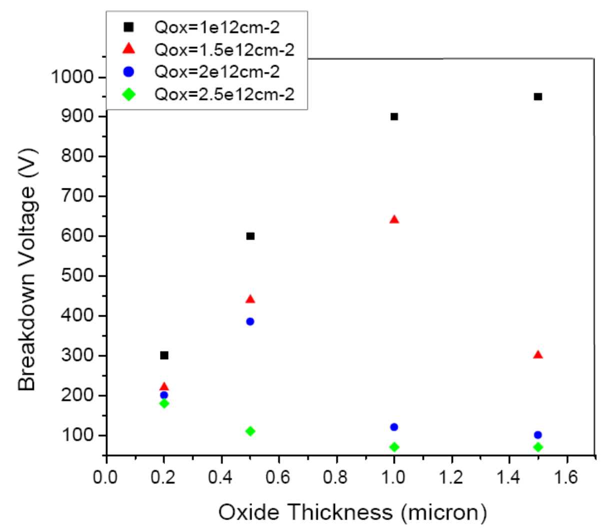
Synopsis Sentaurus used to predict electric field profile / breakdown voltage for various implant/oxide/metal/passivation configurations.
Result sustains V_{bias} = 900 V for $\phi = 10^{15}\ cm^{-2}\ n_{eq}$ and $Q_{ox} < 10^{12}\ cm^{-2}$.





Example optimizations





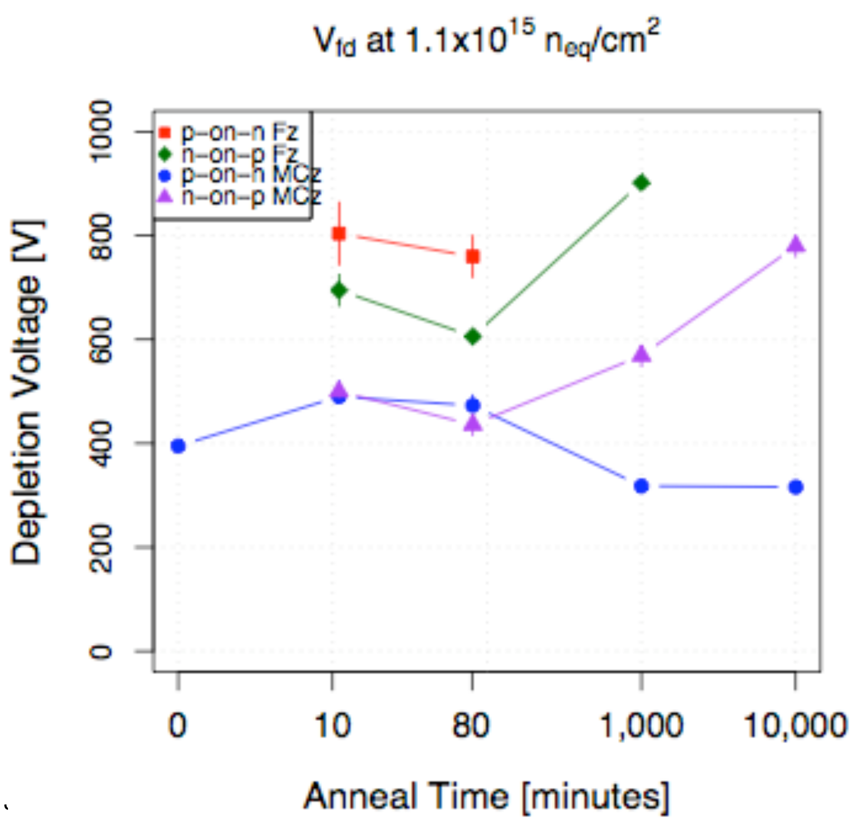
O. Koybasi

p- versus n-type, Float Zone versus Magnetic Czochralski

A study of $V_{full\ dep}$ after p irradiation and annealing

	n-on-p Fz	p-on-n Fz	n-on-p MCz	p-on-n MCz
Manufacturer	HPK	Micron	Micron	Micron
Resistivity	13 kΩ-cm	3.3 kΩ-cm	1.9 kΩ-cm	1.4 kΩ-cm
Active Area	3mmx3mm	3mmx3mm	3mmx3mm	3mmx3mm
Thickness	300 μm	300 μm	300 μm	300 μm
Initial V_{fd} [V]	75	95	520	220

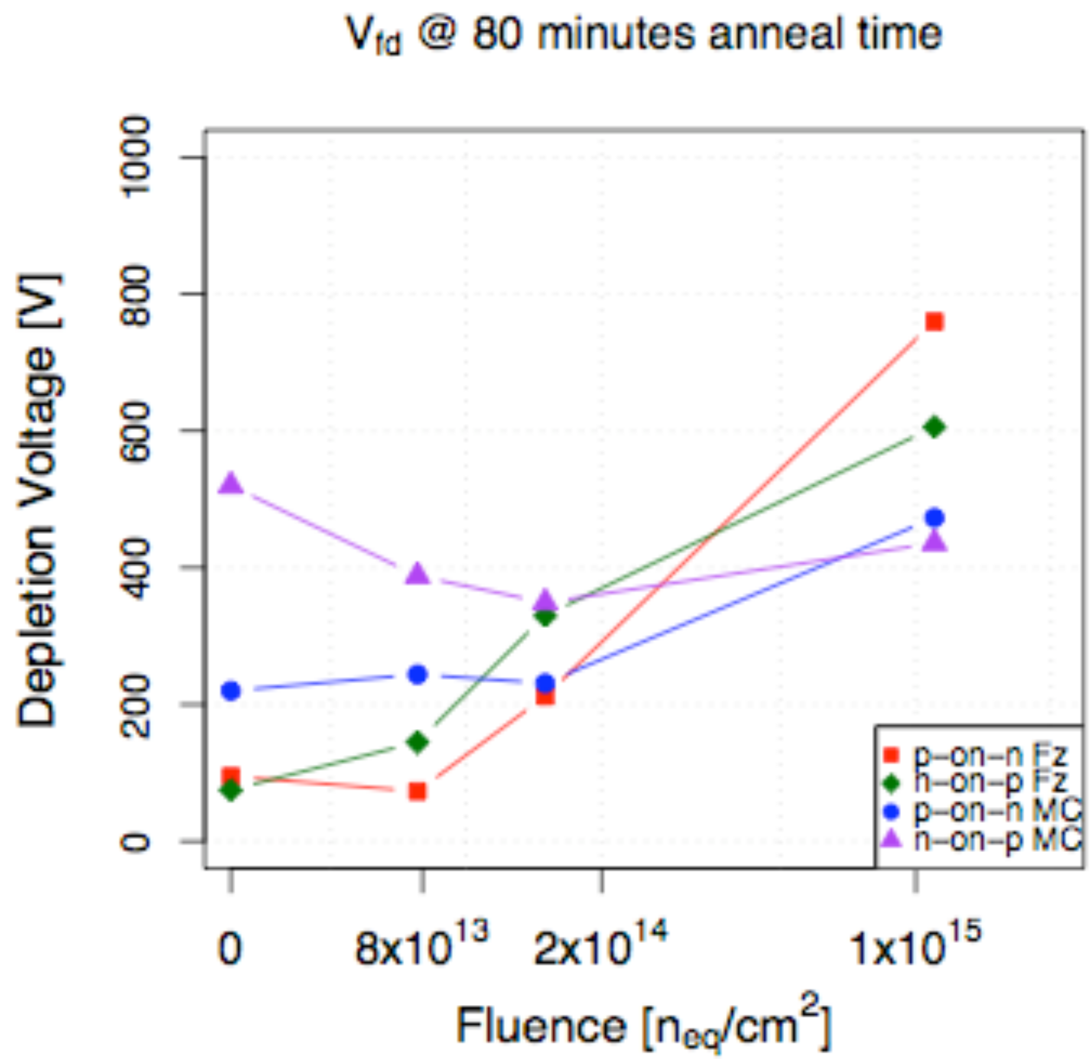
800 MeV p @Los Alamos
60° C anneal



- Beneficial annealing observed for the first 80 minutes anneal time, then V_{fd} begins to increase for samples shown to have neg space charge after proton irradiation:
  - n-on-p Fz
  - p-on-n Fz
  - n-on-p MCz
- p-on-n MCz shows annealing behavior typical of n-type devices that have +sc after proton irradiation.

p- versus n-type, Float Zone versus Magnetic Czochralski, continued

- FZ show greatest increase of V_{fd} with increasing fluence
- n-on-p MCz shows little change



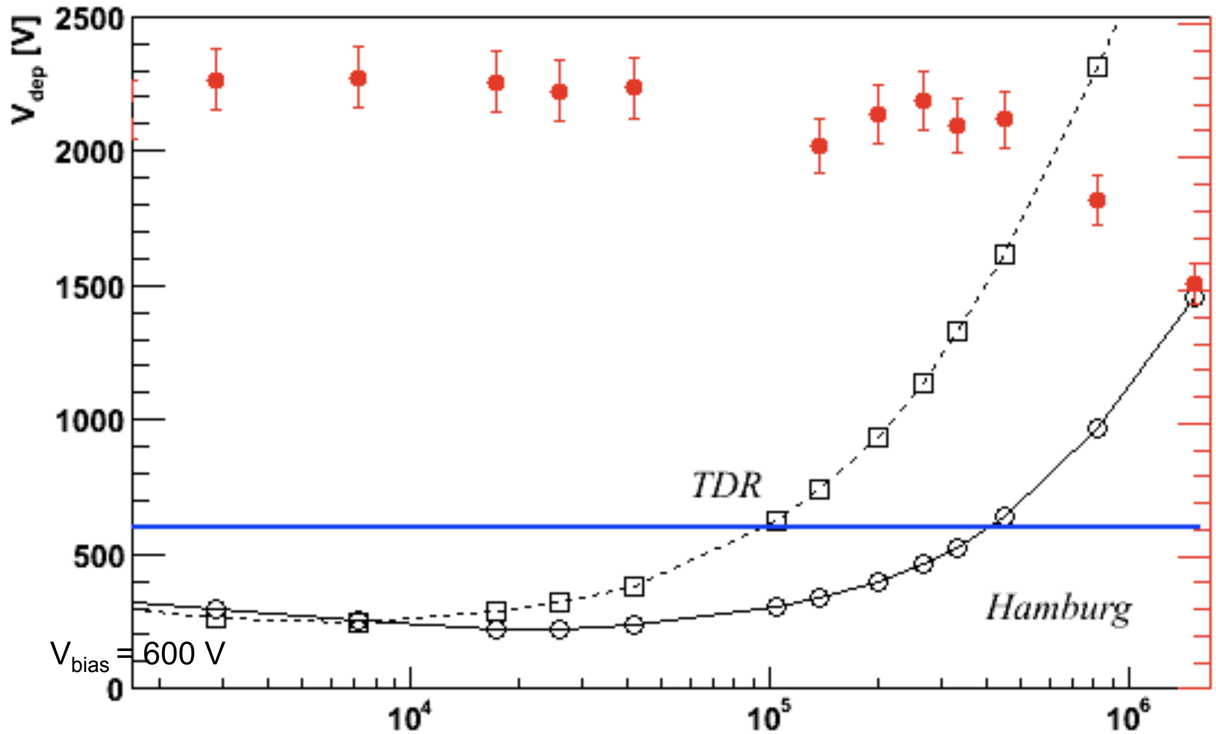
CCE versus annealing of p-in-n sensors

- Motivations: An examination of results for long annealing times, to reduce dependence upon model-based extrapolations; to acquire signal data after high dose and long annealing times, in the regime where CV-based models predict under-depletion.

- FZ, $2x10^{14}$ cm^{-2} n_{eq} @ Ljubljana

Models:

- *ATLAS TDR 5 CERN/LHCC/97-17.*
- *Hamburg model, thesis of M. Moll, 1999.*



A. Affolder, H. Brown, G. Casse, P. Dervan, J. Vossebeld, C. Wigglesworth

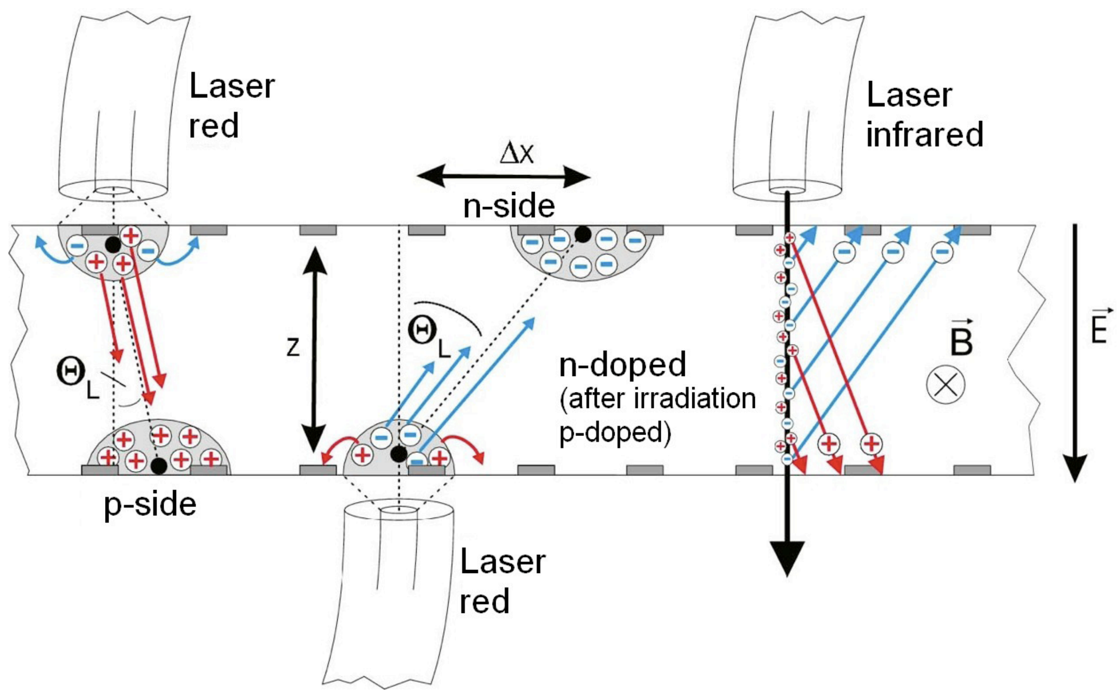
Even when the CV-based models predict significant under-depletion, the signal is still sizeable and diminishes only slowly.

Lorentz angle in silicon strip sensors

	Manufacturer	Material	Thickness [μm]	U_{dep} [V]	Fluence [$\frac{n_{eq}}{cm^2}$]	Pitch[μm]
CMS	ST Microelectronics	FZ n-type	500	154	0	120
2	Micron / RD50	FZ p-type	300	12	0	
000	Micron / RD50	FZ p-type	300	≈ 1000	$1 \cdot 10^{15}$	80
1000	Micron / RD50	FZ p-type	300	> 1000	$9.8 \cdot 10^{15}$	
n-169	HIP	MCz n-type	300	169	$7.1 \cdot 10^{14}$	
n-272	HIP	MCz n-type	300	272	$7.1 \cdot 10^{14}$	
-1000	HIP	MCz n-type	300	> 1000	$7.2 \cdot 10^{15}$	50
47	HIP	MCz n-type	300	347	0	

- 23 MeV p (Karlsruhe)
- Magnet up to 8 T

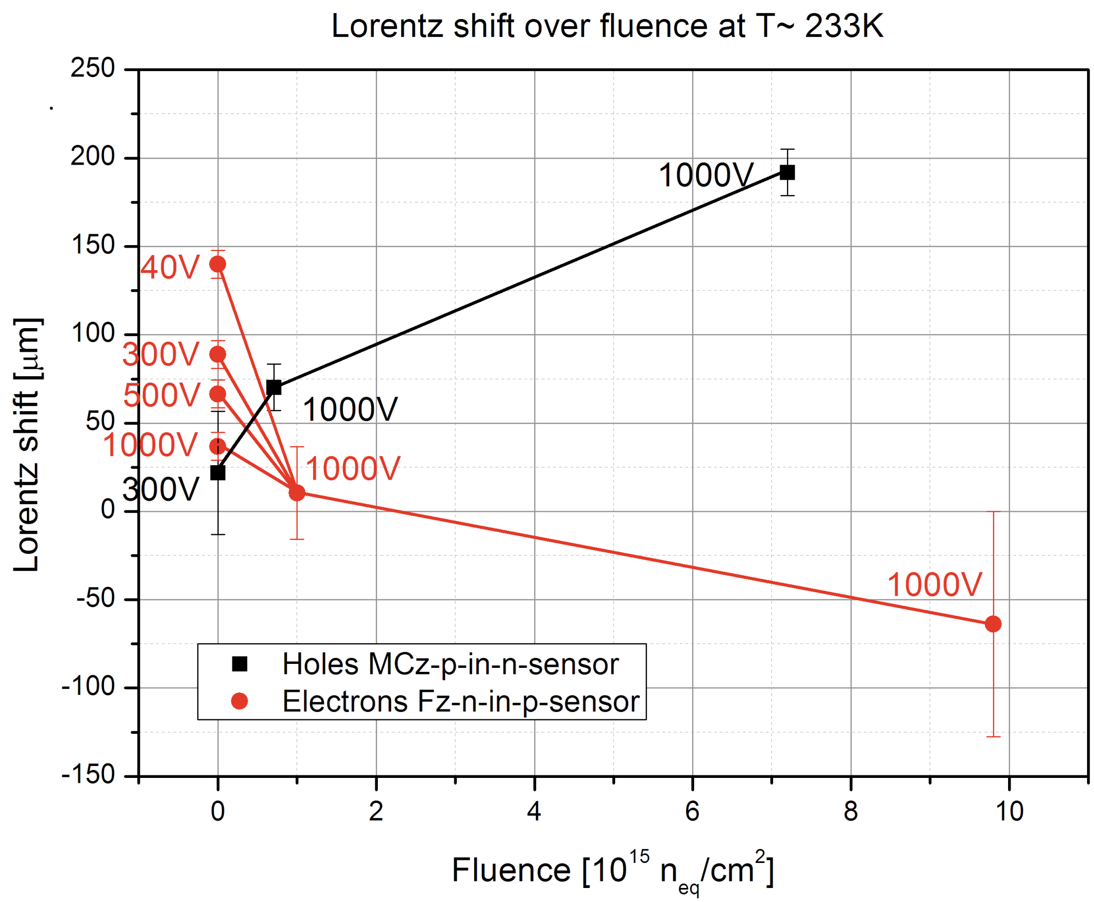
Red laser: best signal
IR laser: MIP-like



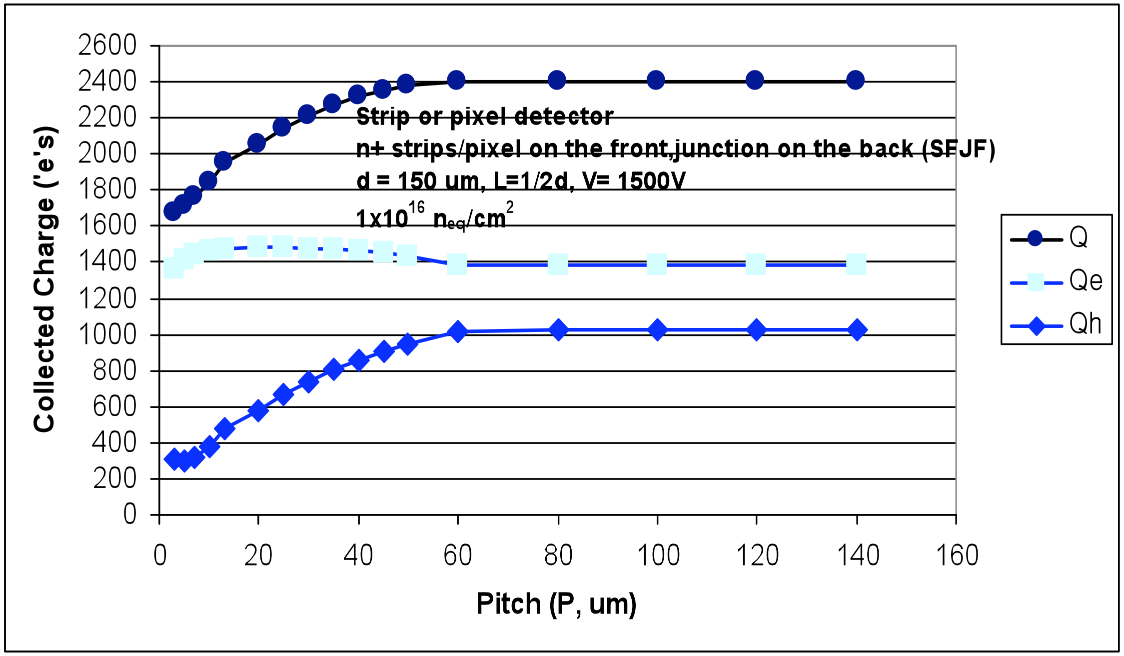
W. de Boer, A. Dierlamm, A. Sabellek, M. Schmanau, M. Schneider

Lorentz angle, continued

Large difference between Lorentz angle for h and e at high fluences---in situ measurement needed for sLHC.



Simulation of the electron and hole contributions to total charge collection in irradiated Si detectors



For P ≥ 60 µm, hole contribution is ~43% due to P >> d_{CCE} or d_t

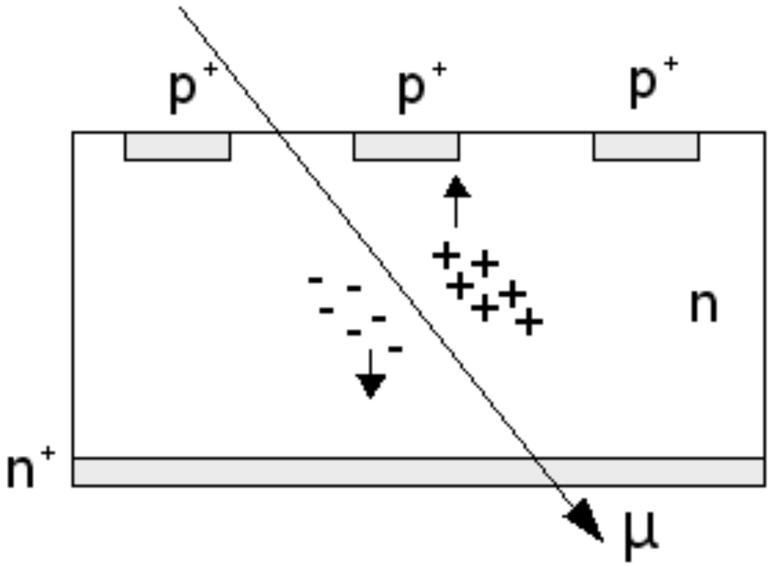
For P < 60 µm, hole contribution decreases as P approaches d_{CCE} or d_t.

Zheng Li

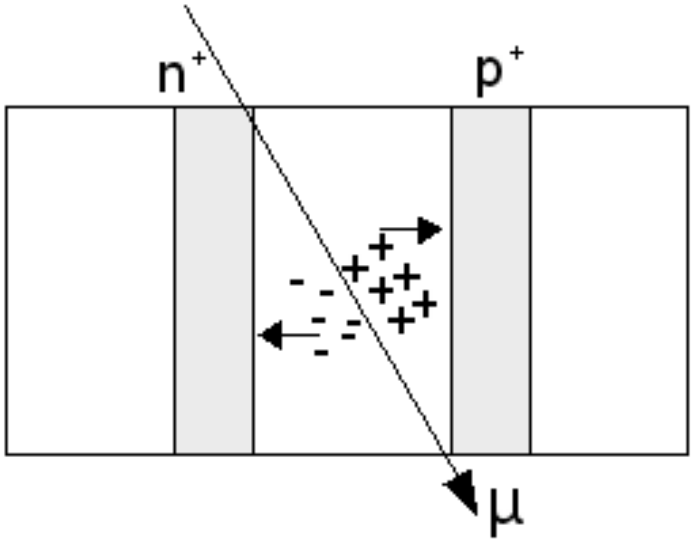
- Contribution of holes to total collected charge increases with fluence in an n^+ segmented Si detector.
- At $1\text{x}10^{16}\ n_{eq}/cm^2$, contribution of holes to total collected charge is comparable to that of electrons.
- At sLHC fluences, total collected charge is approximately $Q = 80e/\mu m \cdot (d^e_{CCE} + d^h_{CCE})$
- To improve radiation hardness, carrier trapping distance has to be increased --- e.g. by pre-filling of the traps or decreasing carrier drift distance (3D).

Sensors with 3D geometry

Motivation: decouple thickness from charge collection distance



Planar

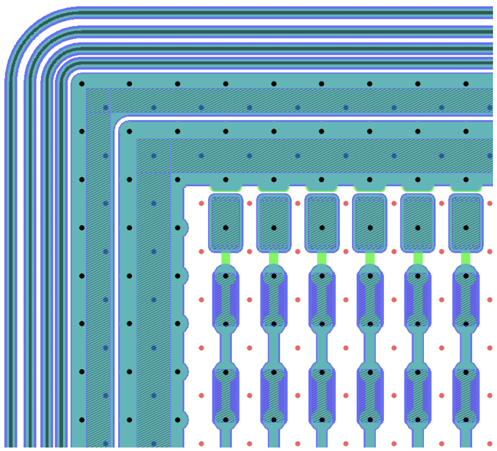


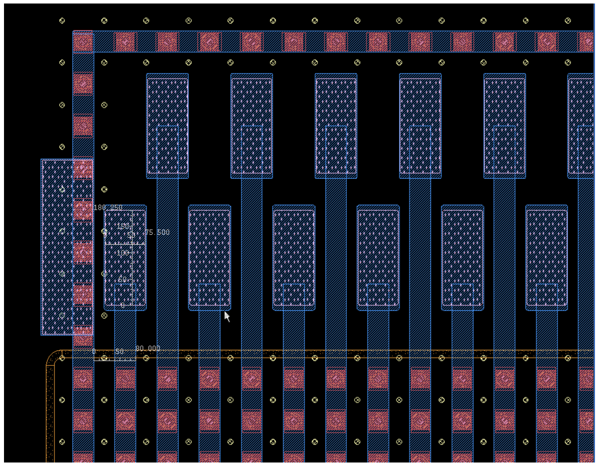
3D

Sensors with 3D geometry

RD50 is examining designs by:

FBK (Trento) and CNM (Barcelona):





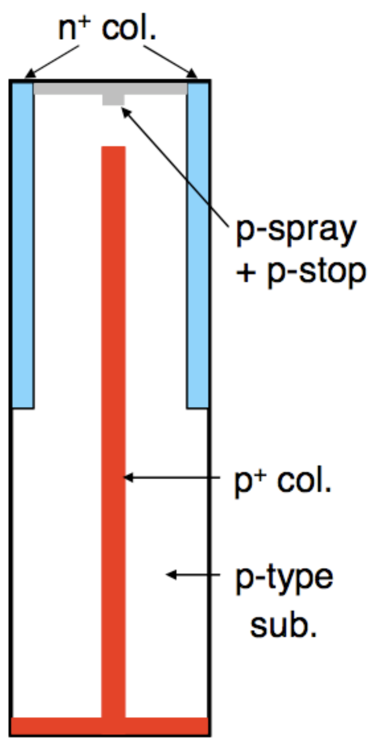
-Columns unfilled
-Ohmic columns connected by uniform n+-doping layer and metallization
-AC and DC coupled readout pads

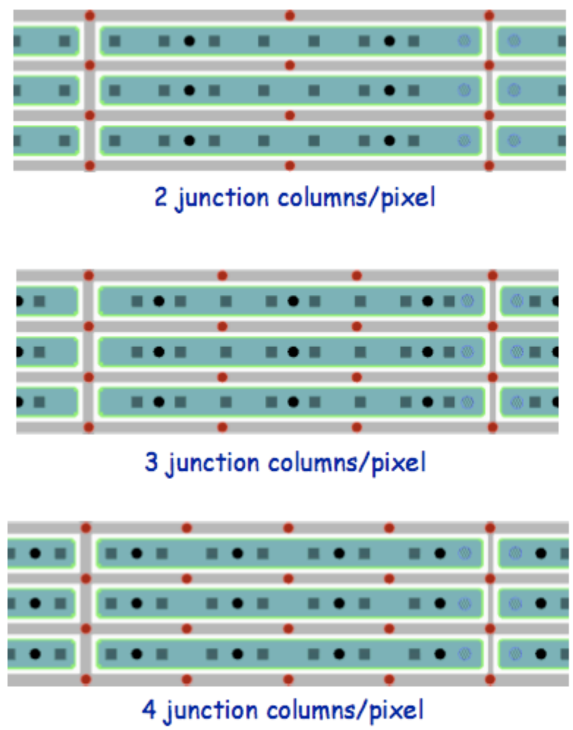
-Columns partially filled with polysilicon
-Ohmic columns connected by polysilicon and metallization
-DC coupled readout pads

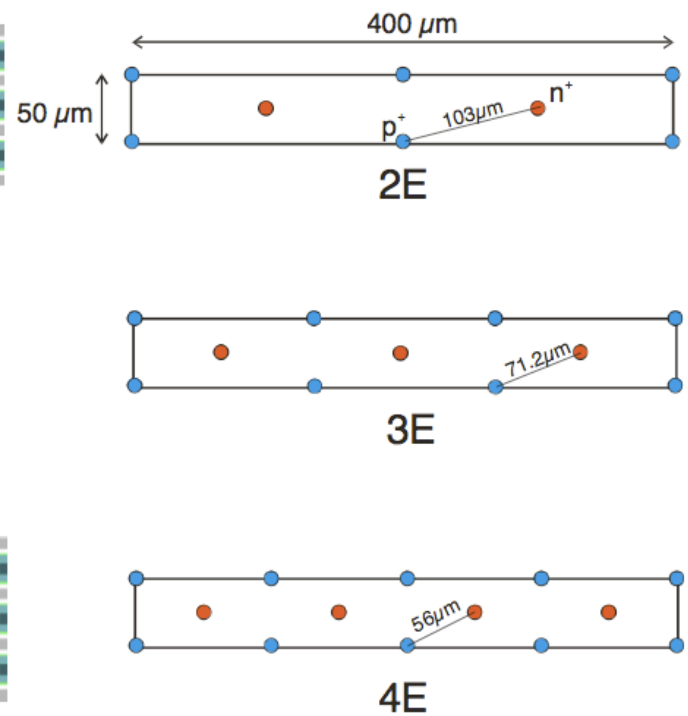
FBK-irst Sensors with 3D geometry

For details please see talk by Per Hansson.

3D-Double side Double Type Column: "ATLAS 3D-DDTC"





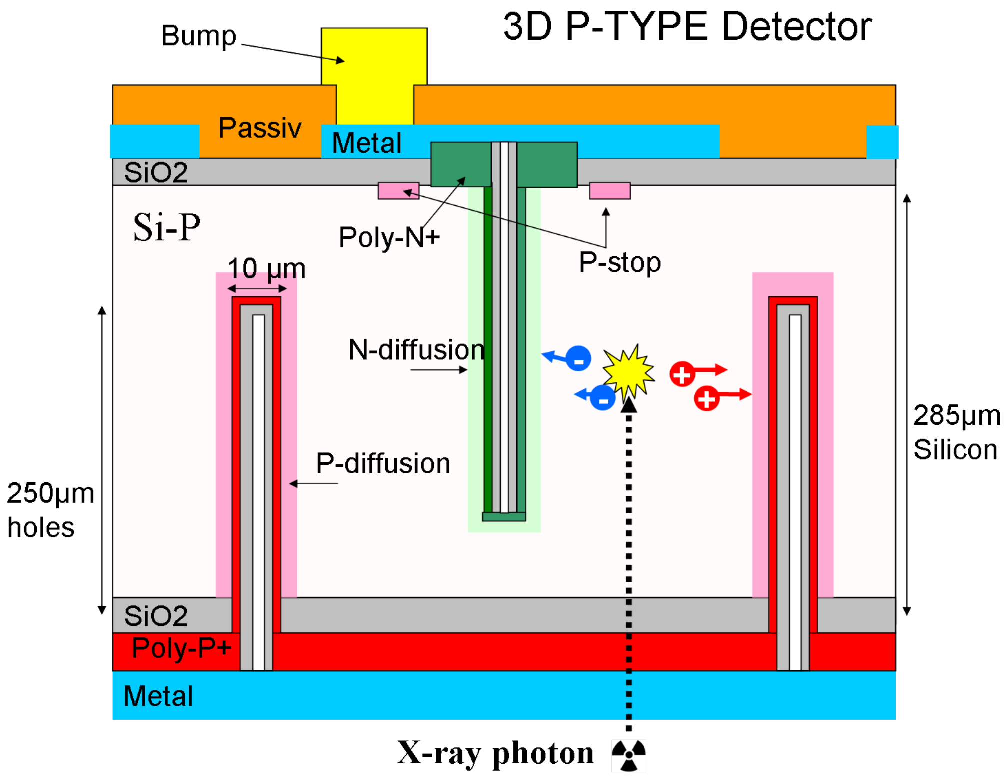


M. Boscardin, G.-F. Dalla Betta, G. Darbo, C. Gemme, A. La Rosa, H. Pernegger, C. Piemonte, M. Povoli, S. Ronchin, A. Zoboli, N. Zorzi

First results show good performance in lab and beam test.

Glasgow/CNM Sensors with 3D geometry

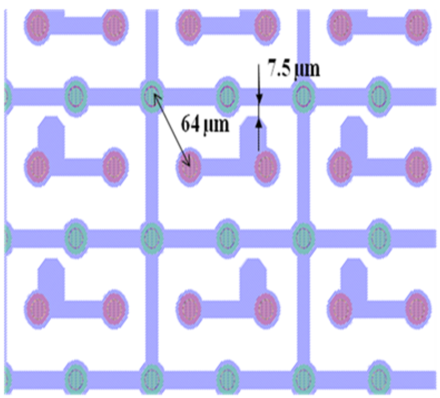
For details please see talk by Giulio Pellegrini.



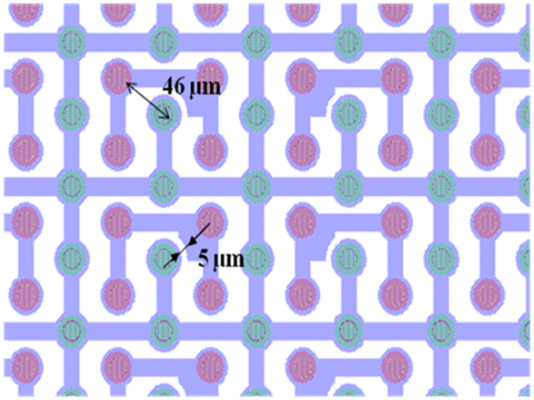
First results show good performance in lab and beam test.

R. Bates, C. Parkes, D. Pennicard, B. Rakotomiaramanana, L. Allanelli, C. Fleta, G. Pellegrini, M. Lozano, U. Parzefll, X. Plot, J. Härkönen, E. Tuovinen

Simulation, Laboratory, and Test Beam Studies of CMS 3D (SINTEF) sensors



2E configuration



4E configuration

Columns become dead regions at $\Phi > 10^{14} n_{eq}\ cm^{-2}$

CCE highest between electrodes (~ 9 ke^- at $\Phi = 10^{16} n_{eq} cm^{-2}$), lowest near cell edges (~ 5.5 ke^- at $\Phi = 10^{16} n_{eq}/cm^2$)

- 2 columns per cell:
  - lower capacitance between readout electrodes (~0.7fF at Φ=0, $Q_{ox}=4x10^{11} cm^{-2}$)
  - less dead volume (~ 4% of total volume)
- 4 columns per cell:
  - faster charge collection
  - less trapping at high fluences
  - lower depletion voltage
  - higher breakdown voltage
  - larger capacitance between readout electrodes (~3.2fF at Φ=0, $Q_{ox}=4x10^{11} cm^{-2}$)
  - larger dead volume (~ 8% of total volume)

O. Koybasi, D. Bortoletto, G. Bolla

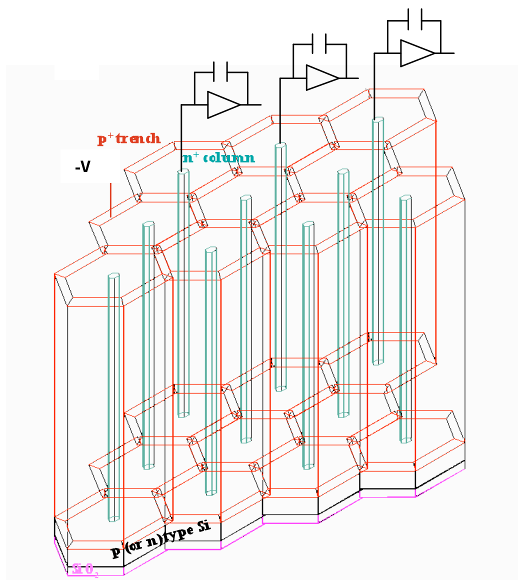
New electrode geometry

- Novel, asymmetric electrode configurations produce homogeneous, well-defined **E**.
- Total collected charge 39%
- Dead space can be reduced to <14% for sLHC

- **Concept of the new Independent Coaxial Detector Array (ICDA) ------** US patent pending (3D-Trench Electrode Detectors), any projects related to this subject must sign official agreements with BNL Office of Technology Commercialization and Partnership (*Kimberley Elcess*, Principal Licensing Specialist, elcess@bnl.gov, 001-631-344-4151)

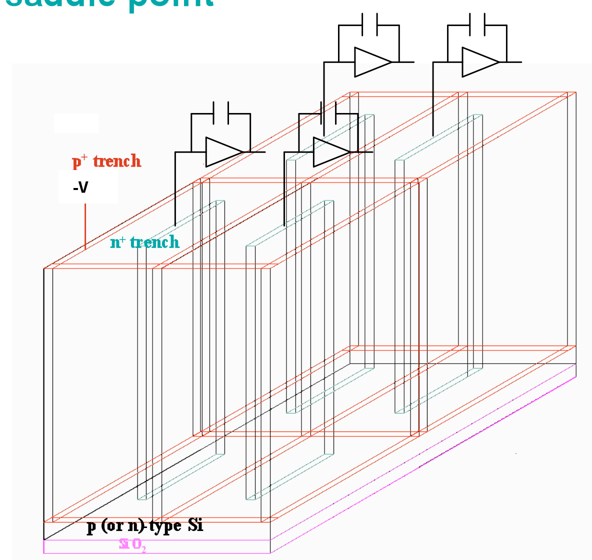
At least one electrode is a trench, each cell can be an independent detector

Homogeneous electric field, no saddle point



Concentric type

Electric field with nearly no θ dependence



Parallel plate type

Near-linear electric field

Zheng Li

Summary

◆Major advances have been made in correlation of microscopic defect properties with observed material properties.

◆New information is provided on epitaxial, Czochralski, and p-bulk silicon substrates.

◆Work is ongoing to understand and optimize Lorentz angle, guard rings, and other design features.

◆New geometries including 3D and Independent Coaxial Detector Array continue to evolve.