Charge Collection Measurements on Irradiated Planar Silicon Strip Sensors

Michel Walz,
Karl Jakobs, Michael Köhler, Ulrich Parzefall, Liv Wiik

Albert-Ludwigs-Universität Freiburg

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Overview

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- Effects on charge collection in irradiated silicon sensors
- Planar p-type strip sensors under test:
  - HPK ATLAS07 series
  - CiS PMS04 sensors
  - CiS MPI epitaxial sensors
- Charge collection measurements done with ALiBaVa readout system at a ^{90}Sr source
- Noise occupancy studies

Irradiation at Karlsruhe irradiation center

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- Irradiation to ATLAS strip detector fluences at sLHC:
  - $5*10^{13}$ n_{eq}/cm^2 (HPK only)
  - $5*10^{14}$ n_{eq}/cm^2
  - $1*10^{15}$ n_{eq}/cm^2
  - $2*10^{15}$ n_{eq}/cm^2
  - $5*10^{15}$ n_{eq}/cm^2 (HPK only)

Thanks to
Wim de Boer &
Alexander Dierlamm

- Irradiation with 25 MeV protons, hardness factor 1.85

- Practically no annealing

Depletion voltages of irradiated sensors

Depletion voltage calculated depending on the effective dopant concentration:

$$V_{FD} = \frac{w^2 q_e \left| N_{eff} \right|}{2\varepsilon\varepsilon_0}$$

After heavy irradiation $|N_{eff}| \approx \Delta N_{eff}$: $\Delta N_{eff} = g_c \cdot \Phi_{eq}$

V. Cindro et al.,
NIM A 599 (2009) 60-65

For proton irradiated FZ silicon: $g_c = 0.012 \pm 0.001$

→ For w = 300 µm, proton irradiated FZ silicon:

V_{FD} (Φ=5*10^{14} n_{eq}/cm^2) ≈ 420 V
V_{FD} (Φ=1*10^{15} n_{eq}/cm^2) ≈ 830 V
V_{FD} (Φ=2*10^{15} n_{eq}/cm^2) ≈ 1770 V
V_{FD} (Φ=5*10^{15} n_{eq}/cm^2) ≈ 4170 V

Impact of trapping on charge collection

After irradiation:
Expected collected charge reduced due to trapping of charge carriers

$$Q \cong Q_0 \cdot \exp\left(\frac{-t_c}{\tau_{tr}}\right) \qquad \frac{1}{\tau_{tr}} = \beta \cdot \Phi_{eq} \qquad \tau_{tr} = \lambda_{av}\left(v_{sat,e}\right)$$

G. Kramberger et al., NIM A 476 (2002) 645-651

Deposited charge in 300 µm silicon: $Q_0 \approx 23$ ke$^-$

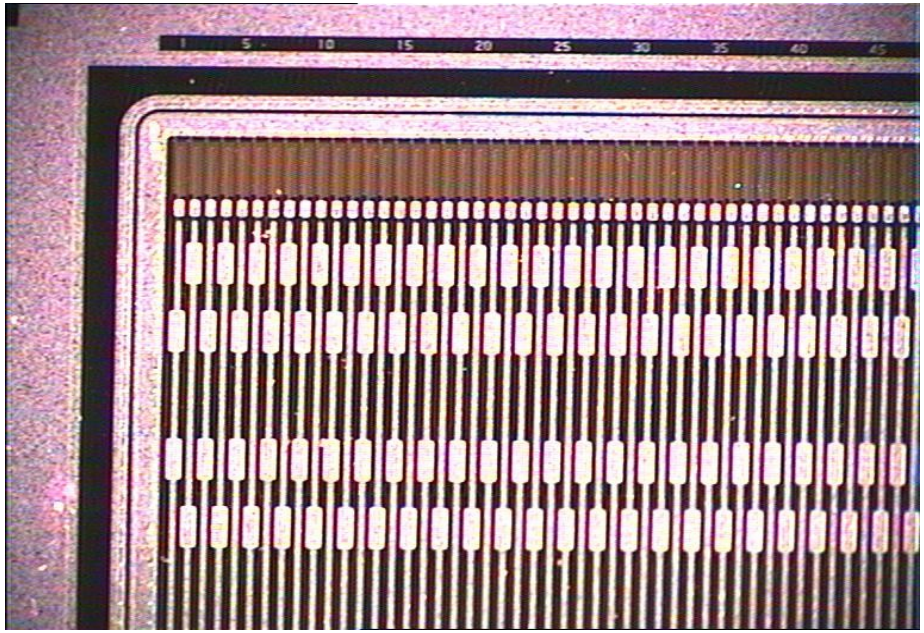
→ Collection distance at saturation velocity (full depletion):

λ_{av} (Φ=5*10^{14} n$_{eq}$/cm^2) ≈ 475 µm	→ trapping not dominant yet
λ_{av} (Φ=1*10^{15} n$_{eq}$/cm^2) ≈ 240 µm	→ Q_{exp} ≈ 19 ke$^-$
λ_{av} (Φ=2*10^{15} n$_{eq}$/cm^2) ≈ 120 µm	→ Q_{exp} ≈ 9 ke$^-$
λ_{av} (Φ=5*10^{15} n$_{eq}$/cm^2) ≈ 50 µm	→ Q_{exp} ≈ 4 ke$^-$

P. Allport et al. "Progress with Planar Silicon Technology for Pixel Layers in ATLAS sLHC", ATLAS Upgrade Week, Nov. 2009

HPK ATLAS07 series

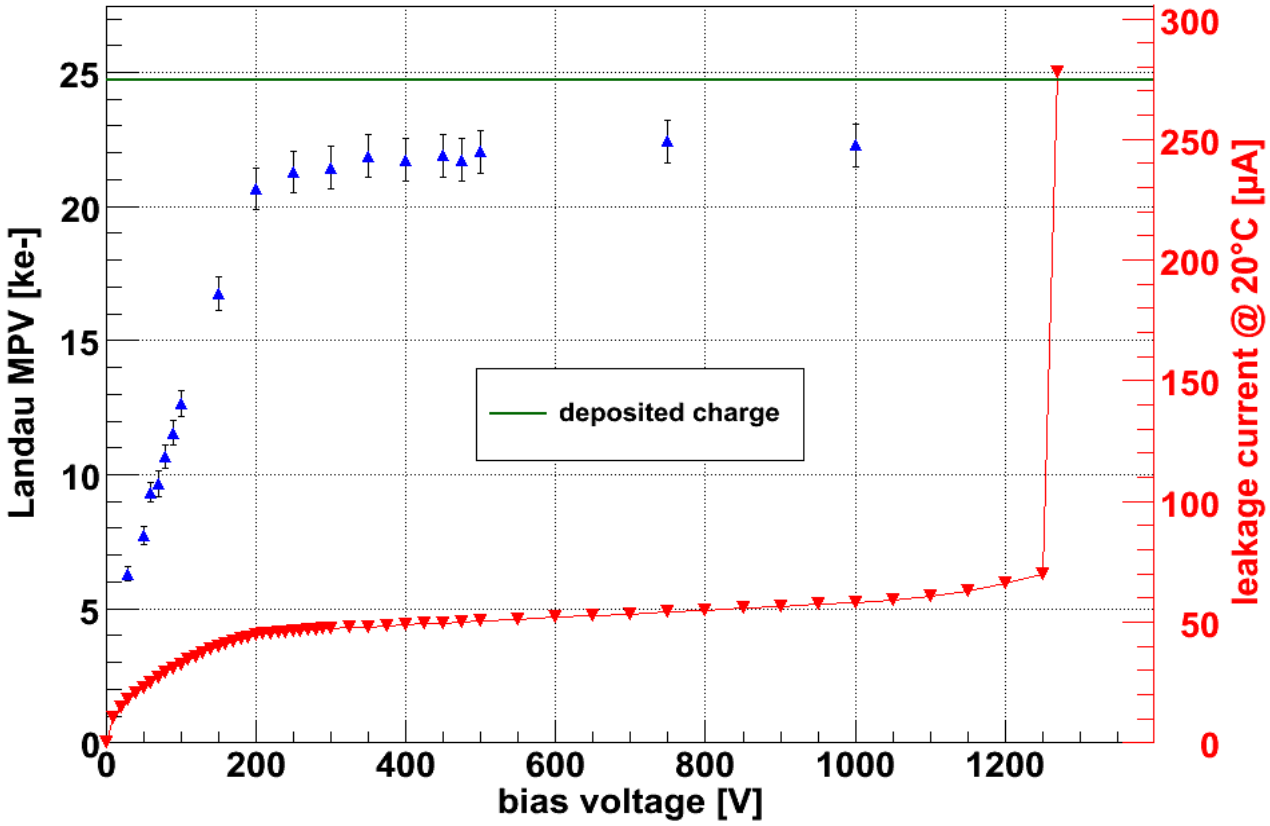
- Miniature sensors, approx. 1x1 cm²
- P-type FZ silicon
- Thickness 320 µm
- 104 strips, strip pitch 74.5 µm
- AC coupling
- Irradiated to
  - $5*10^{13}$ n_{eq}/cm^2
  - $5*10^{14}$ n_{eq}/cm^2
  - $1*10^{15}$ n_{eq}/cm^2
  - $2*10^{15}$ n_{eq}/cm^2
  - $5*10^{15}$ n_{eq}/cm^2



HPK, fluence $5*10^{13}$ n_{eq}/cm^2

- Deposited charge in 320 µm silicon: 24.7 ke^-
- Plateau at approx. (22.4±0.8) ke^- → nearly full charge collected

- $V_{FD} \approx 200$ V
- $V_{Breakdown} = 1270$ V
- Noise = 660 e^-
  → S/N ≈ 34
- T = - 22 °C



HPK, fluence $5*10^{14}$ n_{eq}/cm^2

- Plateau at approx. (19.6±0.7) ke^-

  → approx. 80 % of deposited charge collected

- $V_{FD} \approx 900$ V

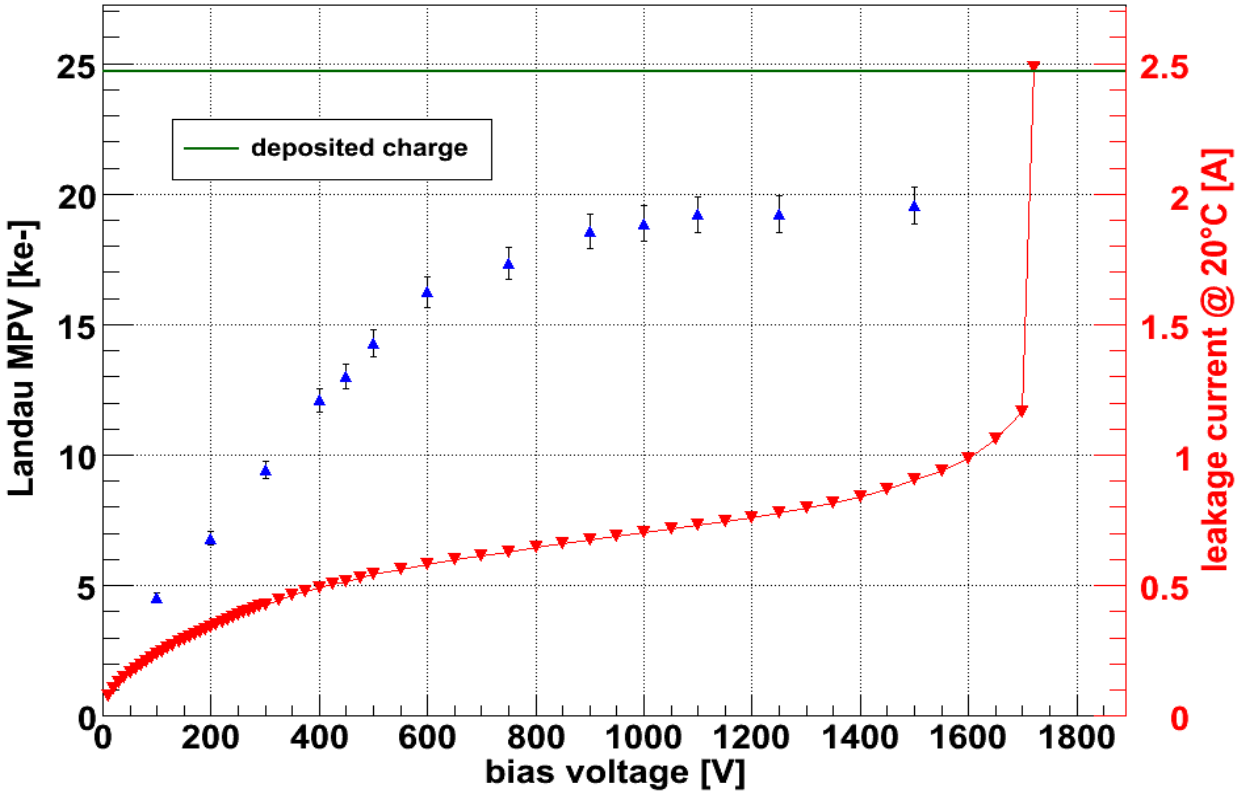
  $V_{FD,calc} = 475$ V

- $V_{Breakdown} = 1660$ V

- Noise = 660 e^-

  → S/N ≈ 30

- T = - 21 °C



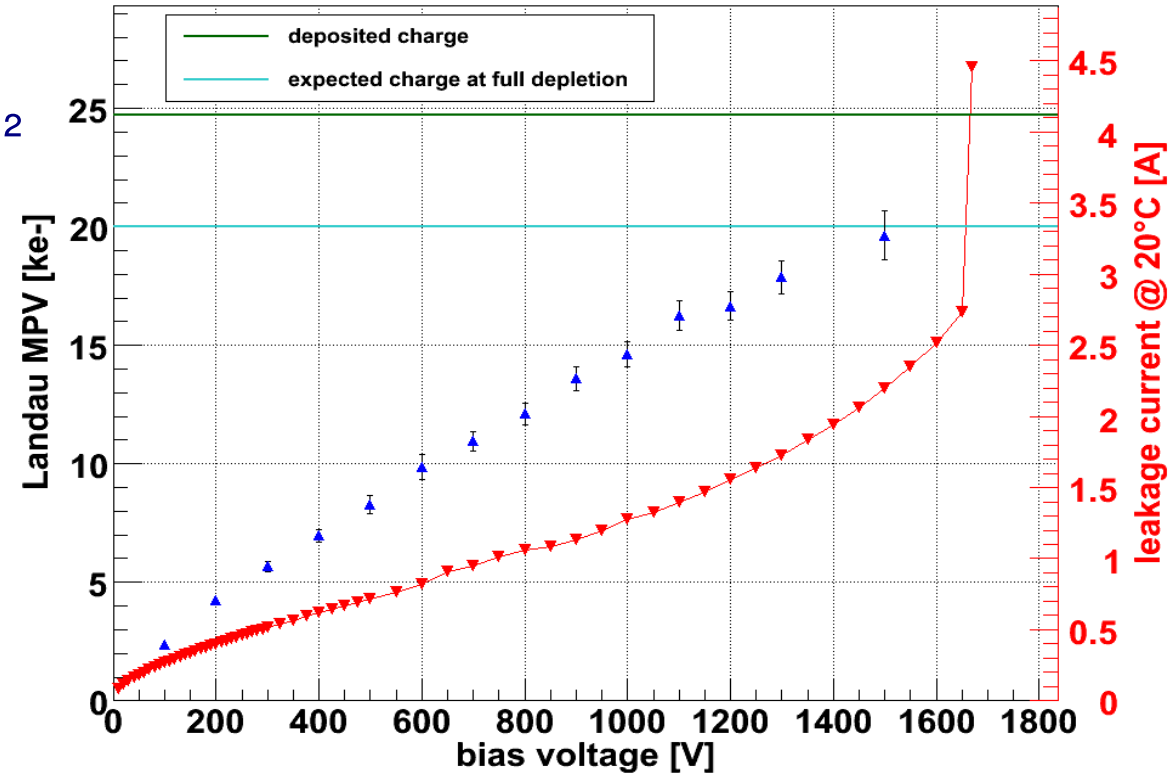
HPK, fluence $1*10^{15}$ n_{eq}/cm^2

- Maximum charge at 1500 V, approx. (19.6±1.0) ke^-
  → matches estimated charge due to trapping (~ 20 ke^-)

- At 1500 V same signal as $5*10^{14}$ n_{eq}/cm^2

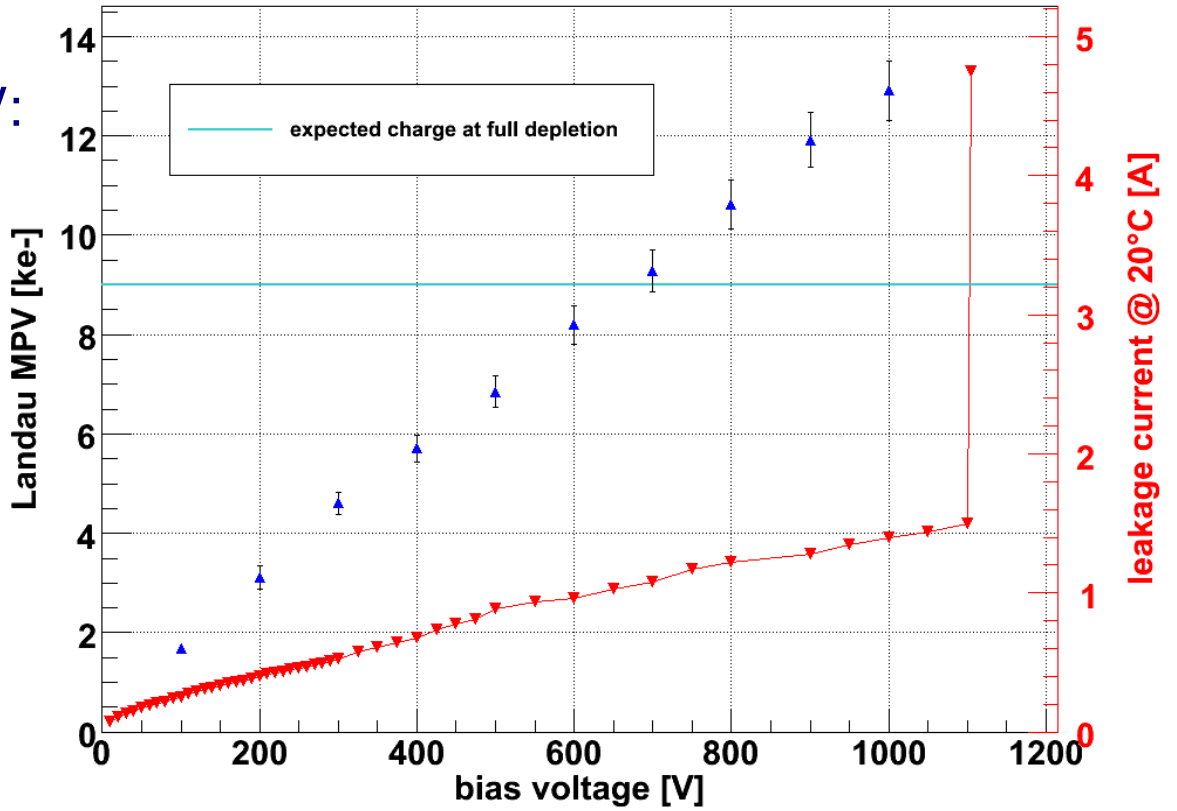
- $V_{FD,calc}$ = 950 V
- $V_{Breakdown}$ = 1660 V
- Noise = 680 e^-
  → S/N ≈ 29

- T = - 21 °C



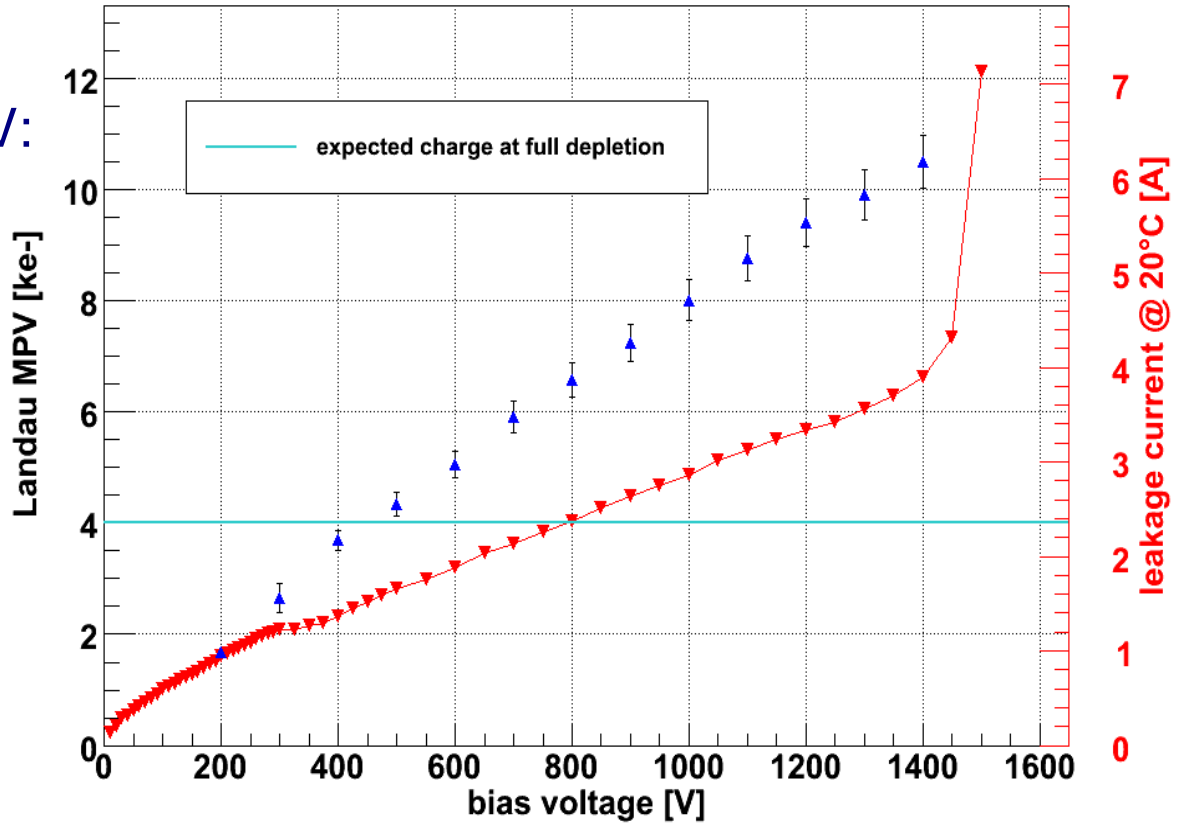
HPK, fluence $2*10^{15}$ n_{eq}/cm^2

- Maximum charge at 1000 V, approx. (12.9±0.6) ke$^-$
  - → 40 % more than estimated charge, although not fully depleted!
- $V_{FD,calc}$ = 1900 V
- Depletion zone at 1000 V:
  - d ≈ 230 µm
- $V_{Breakdown}$ = 1100 V
- Noise = 610 e$^-$
  - → S/N ≈ 21
- T = - 40 °C



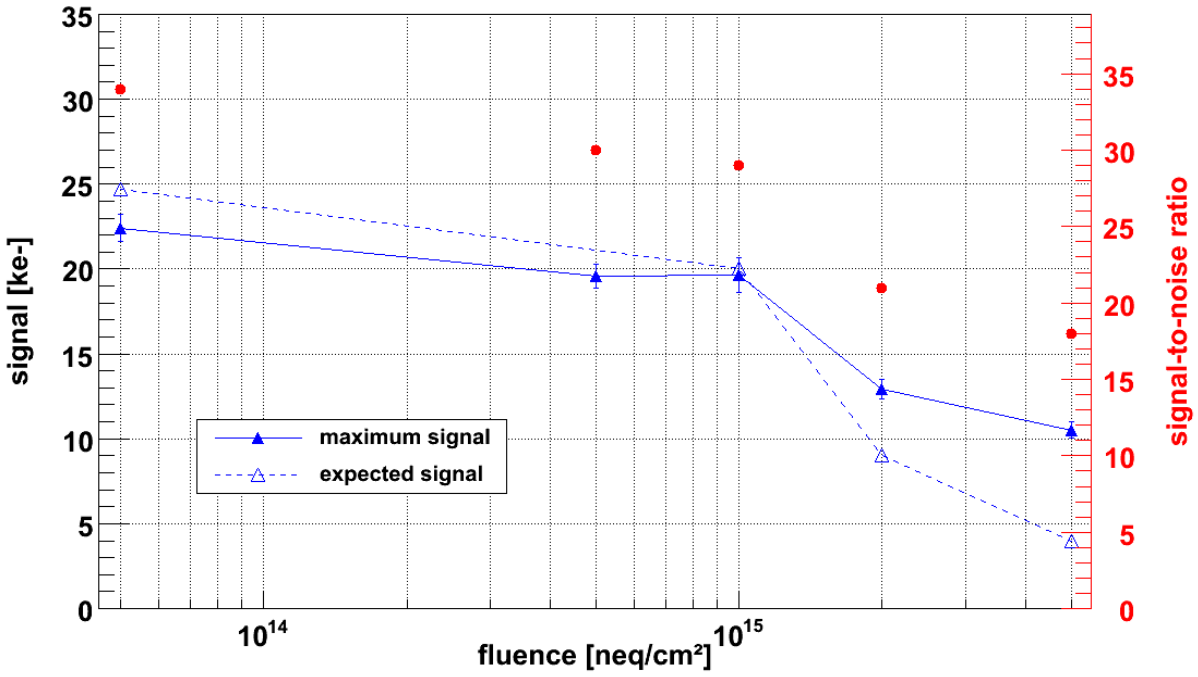
HPK, fluence $5*10^{15}$ n_{eq}/cm^2

- Maximum charge at 1400 V, approx. (10.5±0.5) ke$^-$
  - → 160 % more than estimated charge, although not fully depleted!
- $V_{FD,calc}$ = 4750 V
- Depletion zone at 1400 V:
  - d ≈ 175 µm
- $V_{Breakdown}$ = 1100 V
- Noise = 580 e$^-$
  - → S/N ≈ 18
- T = - 40 °C



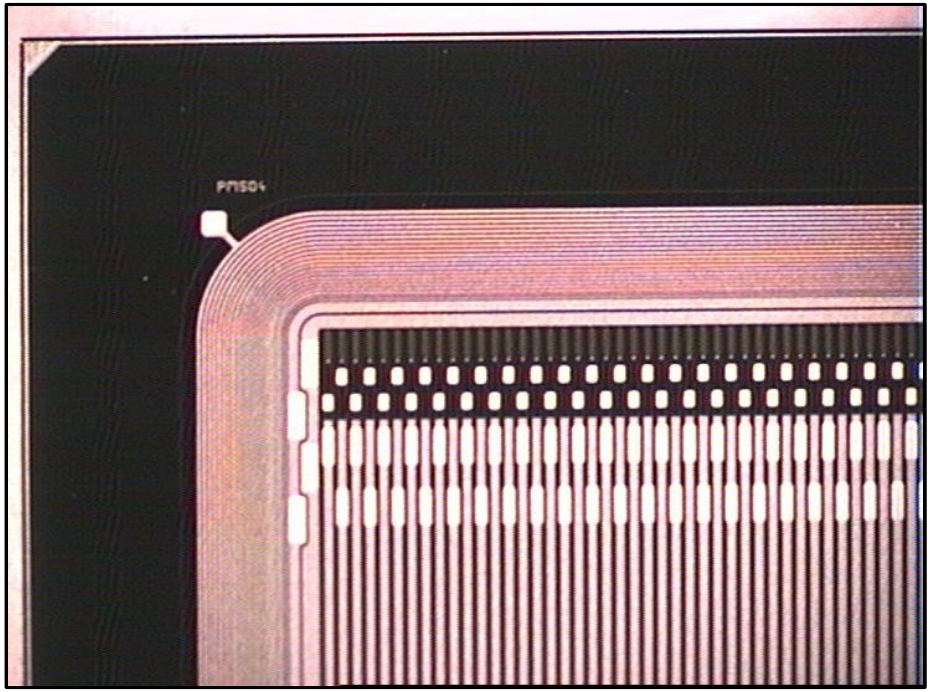
HPK results, signal vs. fluence

- Same maximum signal for $5*10^{14}$ n_{eq}/cm^2 and $1*10^{15}$ n_{eq}/cm^2
- Trapping model not precise for high fluences?
- Other effect besides trapping affects charge collection
  → charge amplification at high fluences?



CiS PMS04 sensors

- Miniature sensors, approx. 1.5x3.5 cm²
- Strip length ~ 3 cm
- P-type FZ silicon
- Thickness 300 µm
- 128 strips, strip pitch 80 µm
- AC coupling
- Irradiated to
  - $5*10^{14}$ n_{eq}/cm^2
  - $1*10^{15}$ n_{eq}/cm^2
  - $2*10^{15}$ n_{eq}/cm^2

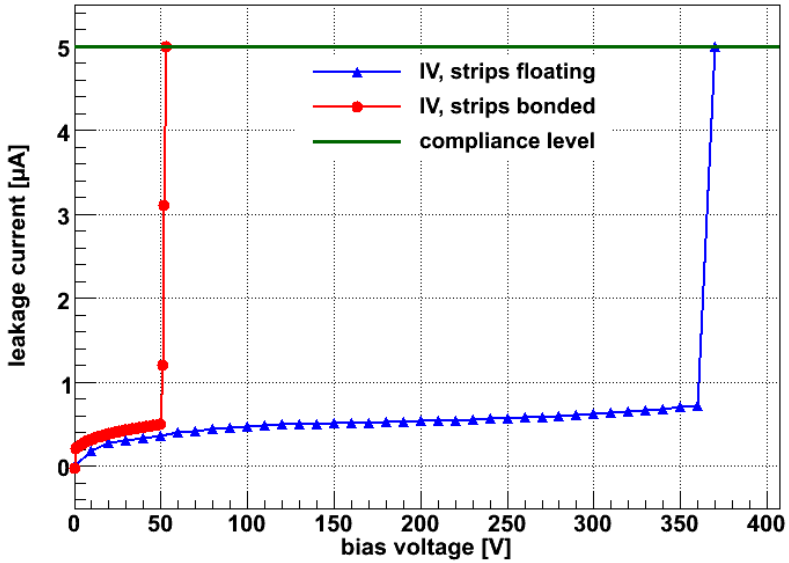


CiS PMS04

Before irradiation:

Biasing problems,

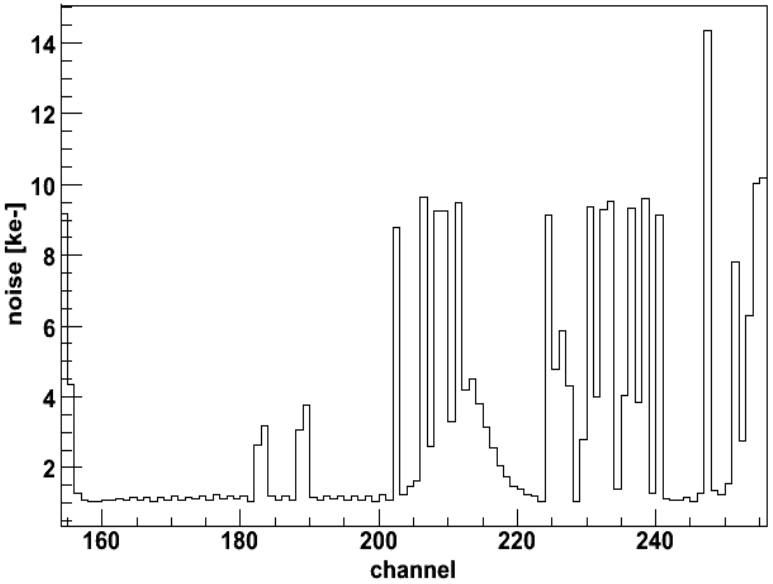
early breakdown if strips bonded



After irradiation:

Micro discharges (> 200 V),

→ huge noise



$\Phi = 5*10^{14}\ n_{eq}/cm^2$, 500 V

Reason unknown!

CiS PMS04, fluence $5*10^{14}$ n_{eq}/cm^2

- Plateau at approx. (17.7±0.8) ke^-

  → approx. 75 % of deposited charge (23 ke^-) collected

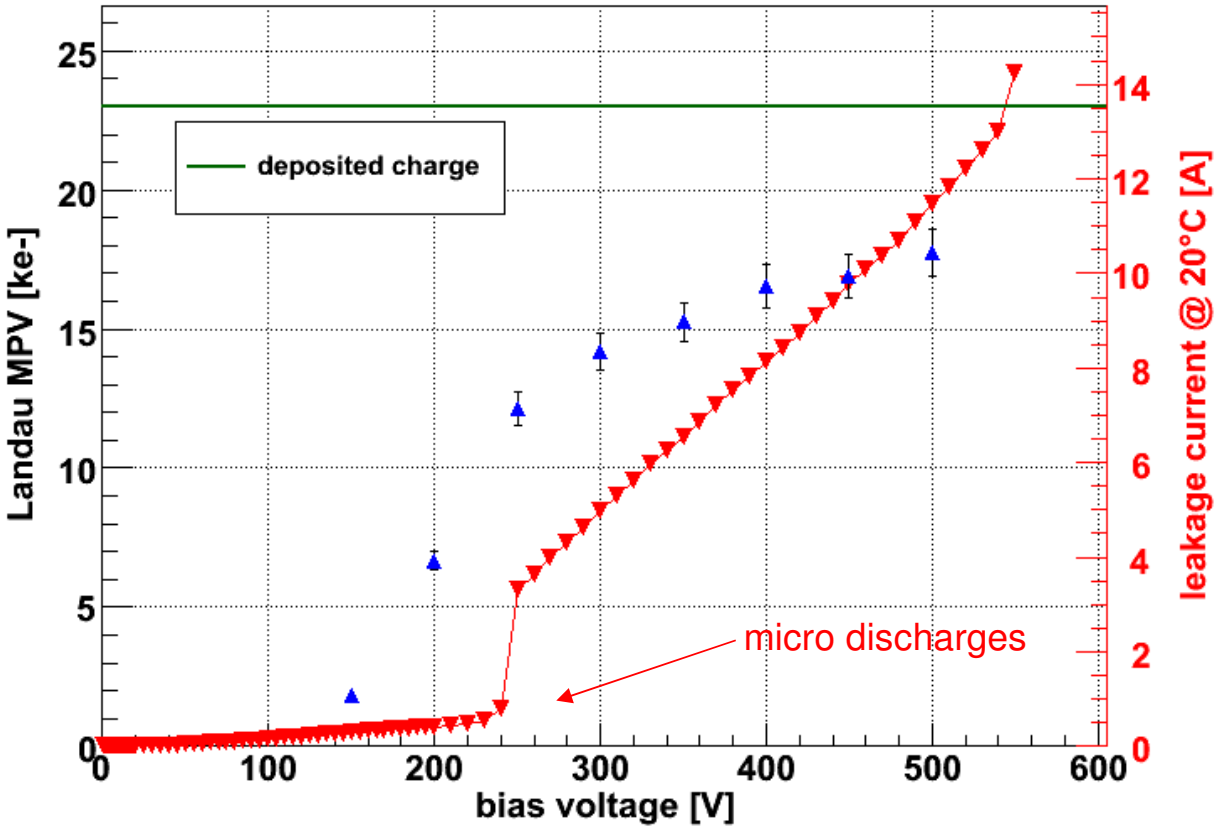
- $V_{FD} \approx 400$ V

  $V_{FD,calc} = 420$ V

- Noise = 910 e^-

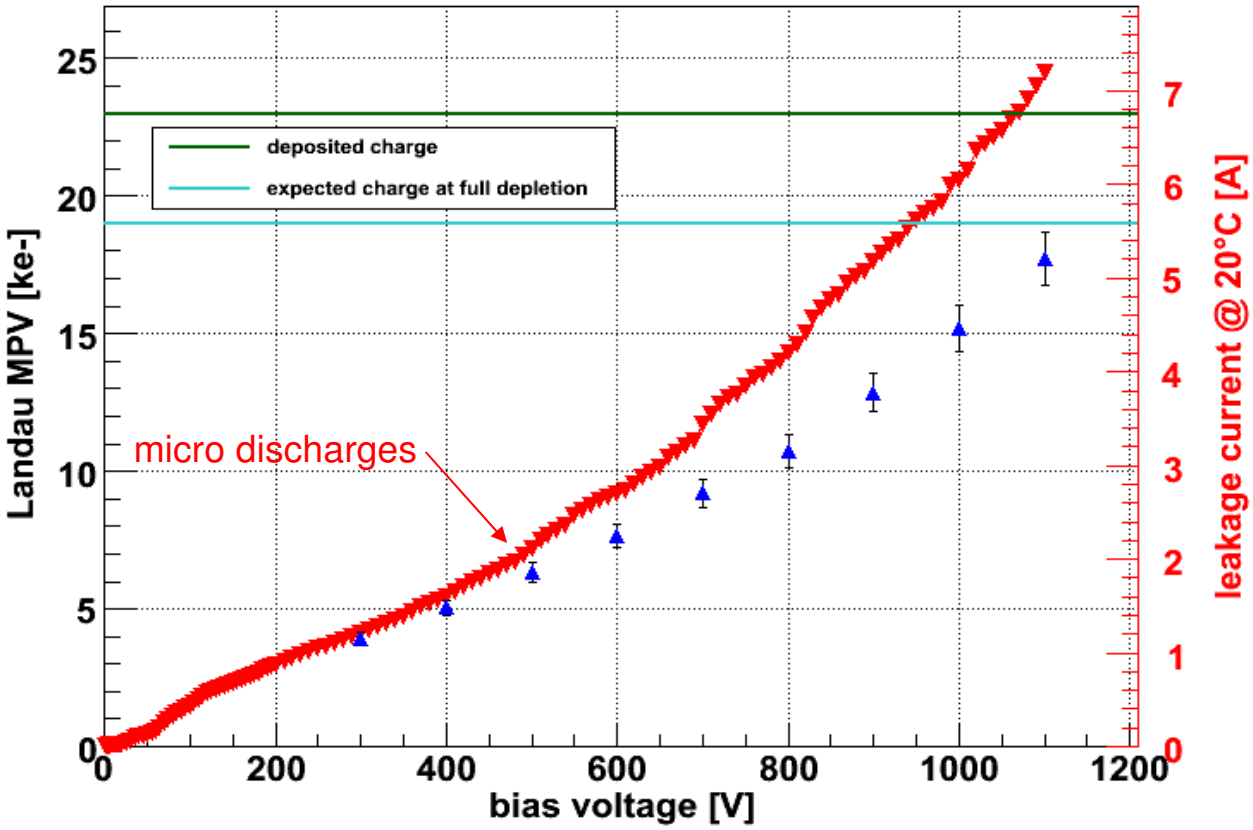
  → S/N ≈ 19

- T = - 40 °C



CiS PMS04, fluence $1*10^{15}$ n_{eq}/cm^2

- Maximum charge at 1100 V, approx. (17.7±1.0) ke$^-$
  → nearly full estimated charge due to trapping (~ 19 ke$^-$) collected
- Same maximum charge as $5*10^{14}$ n_{eq}/cm^2
- $V_{FD,calc}$ = 830 V
- Noise = 860 e$^-$
  → S/N ≈ 21
- T = - 50 °C



CiS PMS04, fluence $2*10^{15}$ n_{eq}/cm^2

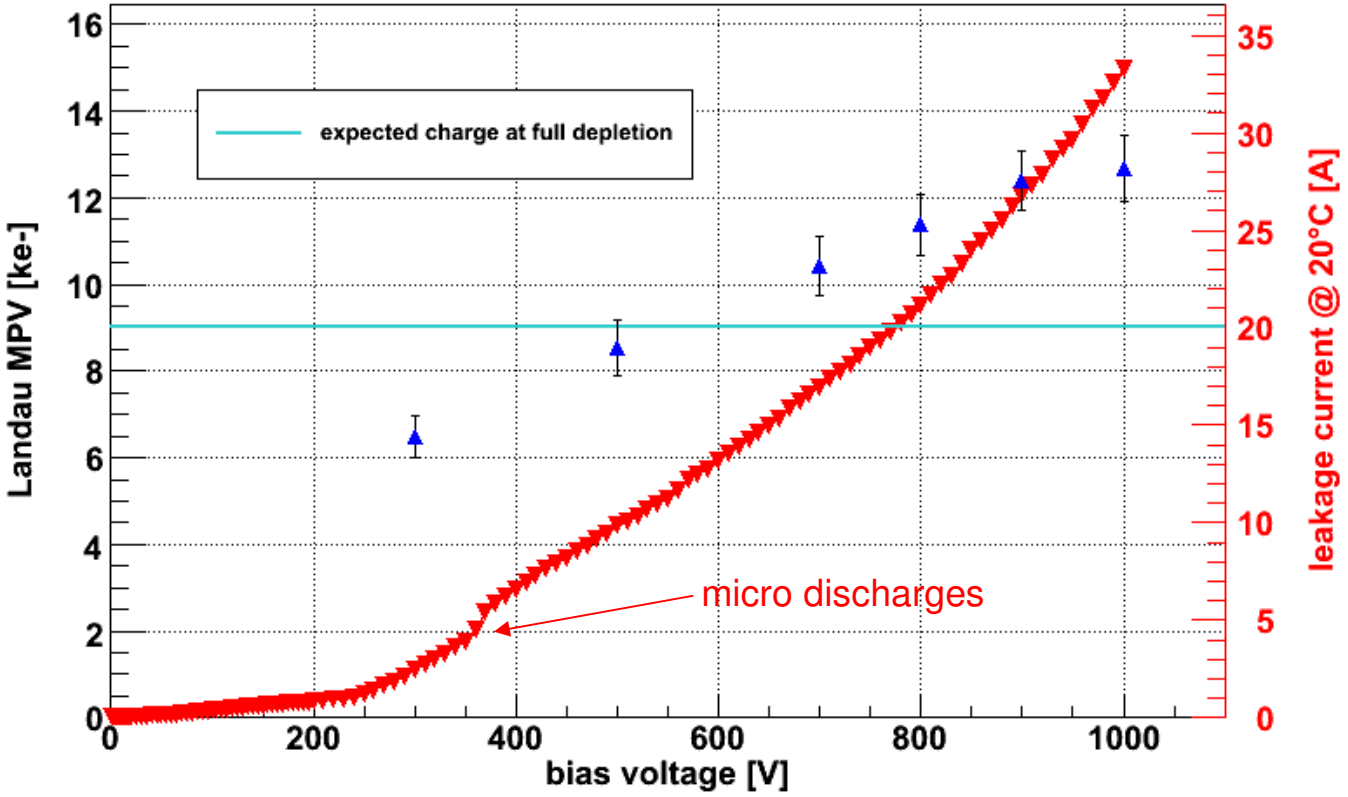
- Maximum charge at 1000 V, approx. (12.7±0.8) ke^-
  - → 30 % more than estimated charge, although not fully depleted!

- $V_{FD,calc}$ = 1770 V

- Depletion zone at 1000 V: d ≈ 230 µm

- Noise = 1.3 ke^-
  - → S/N ≈ 10

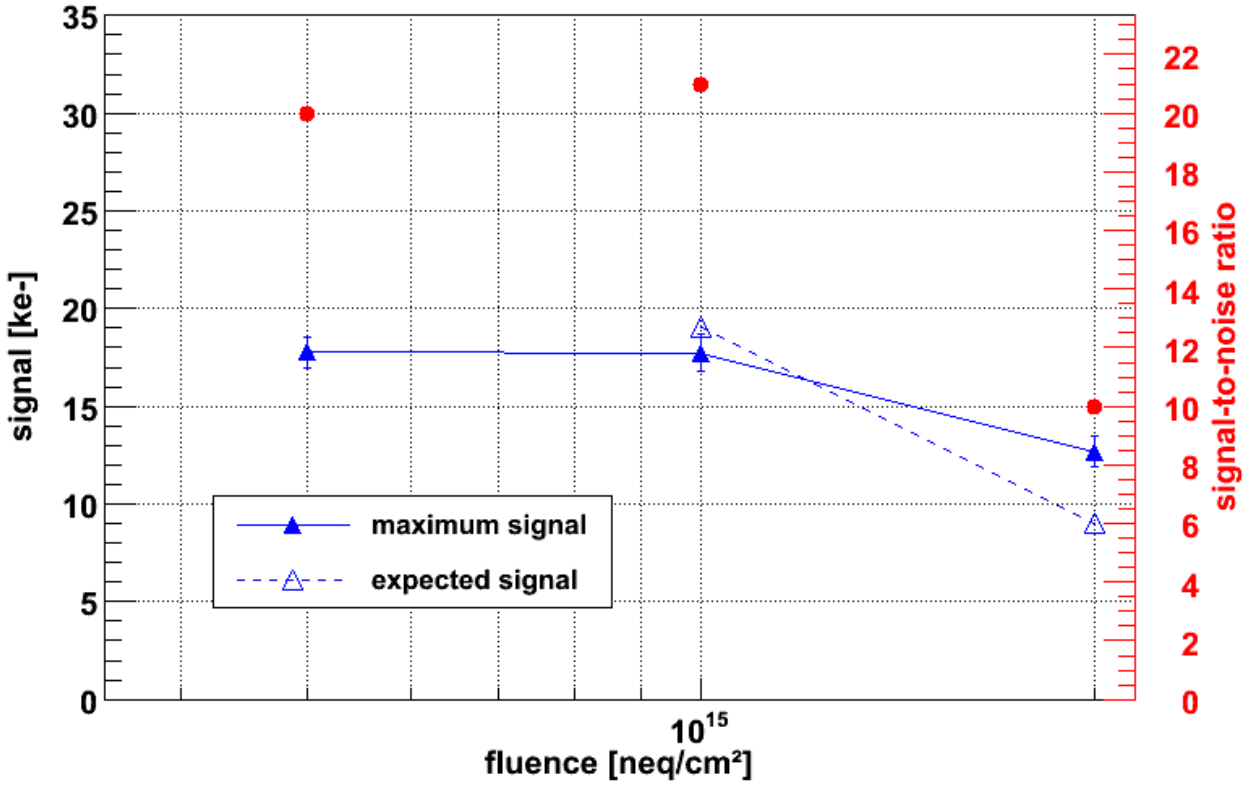
- T = - 42 °C



CiS PMS04 results, signal vs. fluence

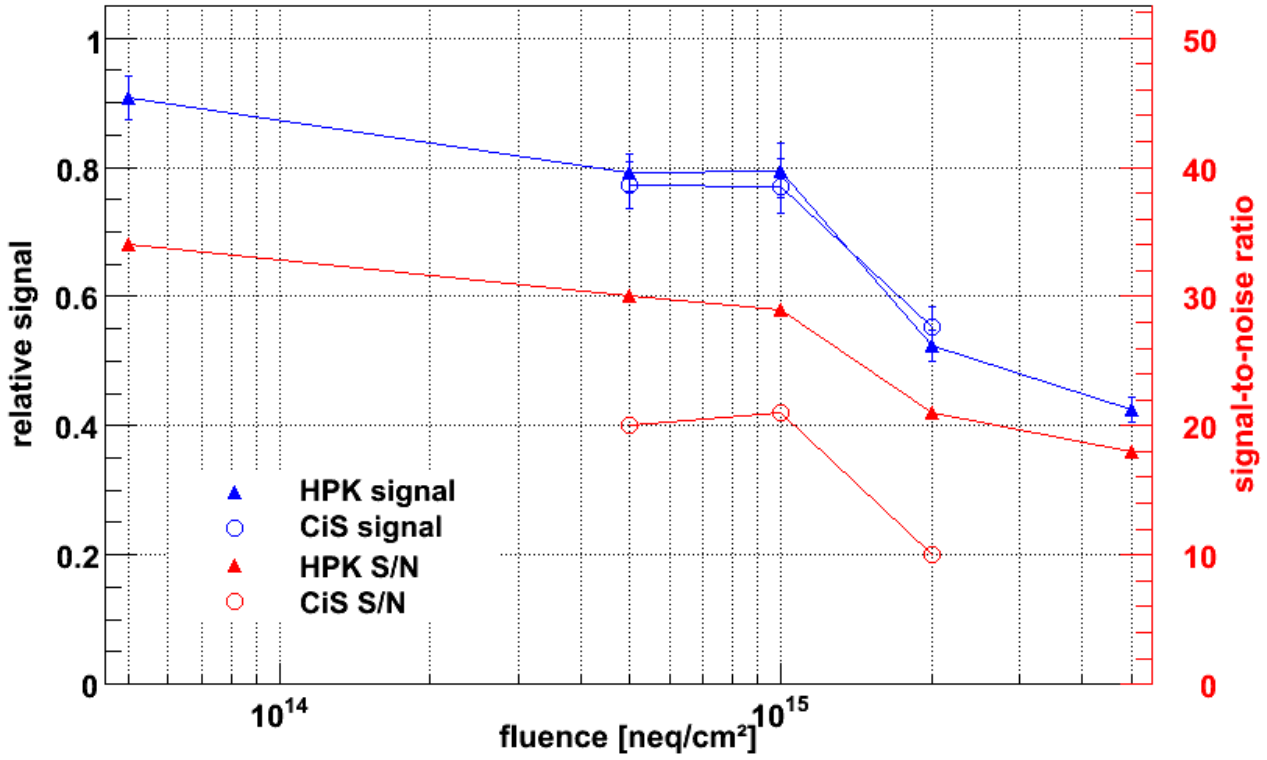
- For $\Phi > 1*10^{15}$ n_{eq}/cm^2 more charge is seen than estimated from trapping

  → Same behaviour as HPK ATLAS07



Comparison CiS PMS04 & HPK ATLAS04

- Very silimar relative signal (normalized on deposited charge)
- Lower signal-to-noise ratio for CiS PMS04, probably due to longer strips → higher capacitance, higher noise

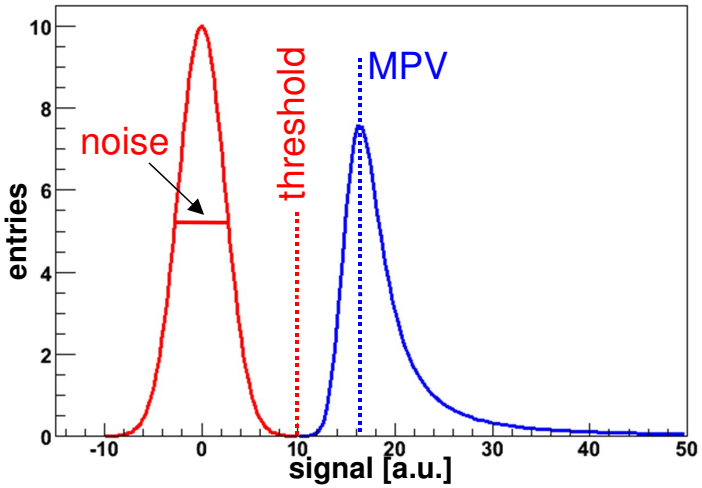


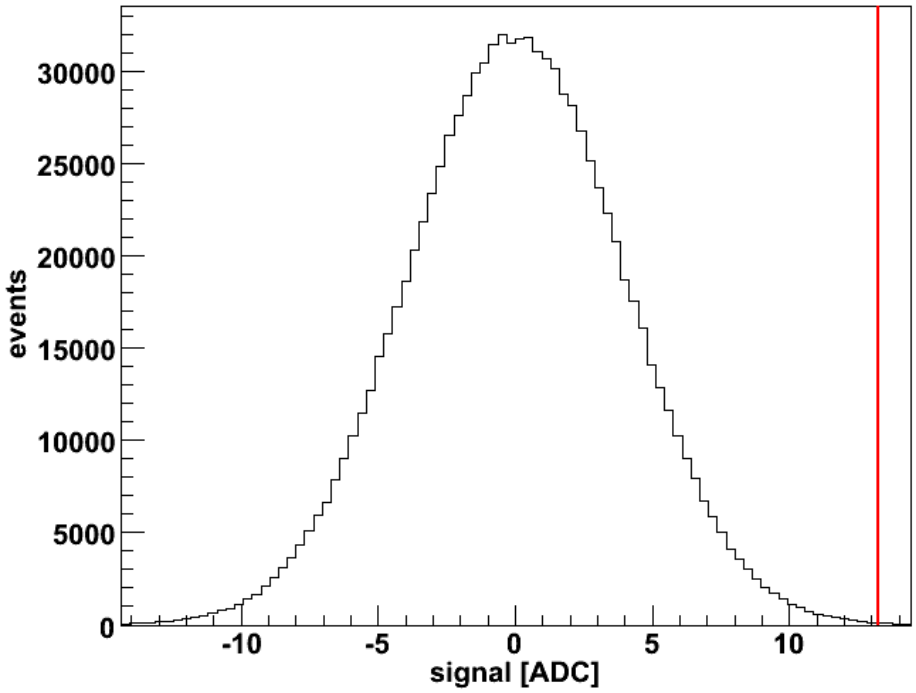
Noise occupancy

- Signal-to-noise ratio only matching criterion for analogue systems
- Binary systems as used in ATLAS SCT detect signal above a certain threshold

  → Signal-to-threshold ratio

- Threshold calculated from noise occupancy

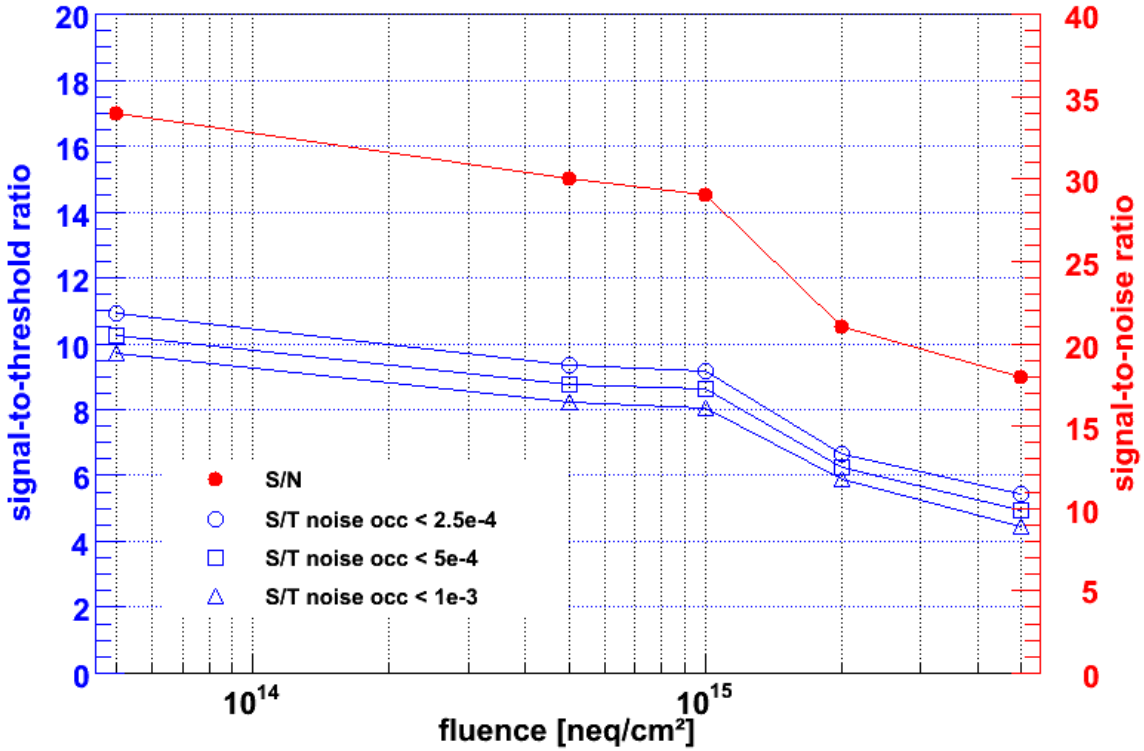




HPK 5*10^{13} n_{eq}/cm², 1000 V

HPK noise occupancy results

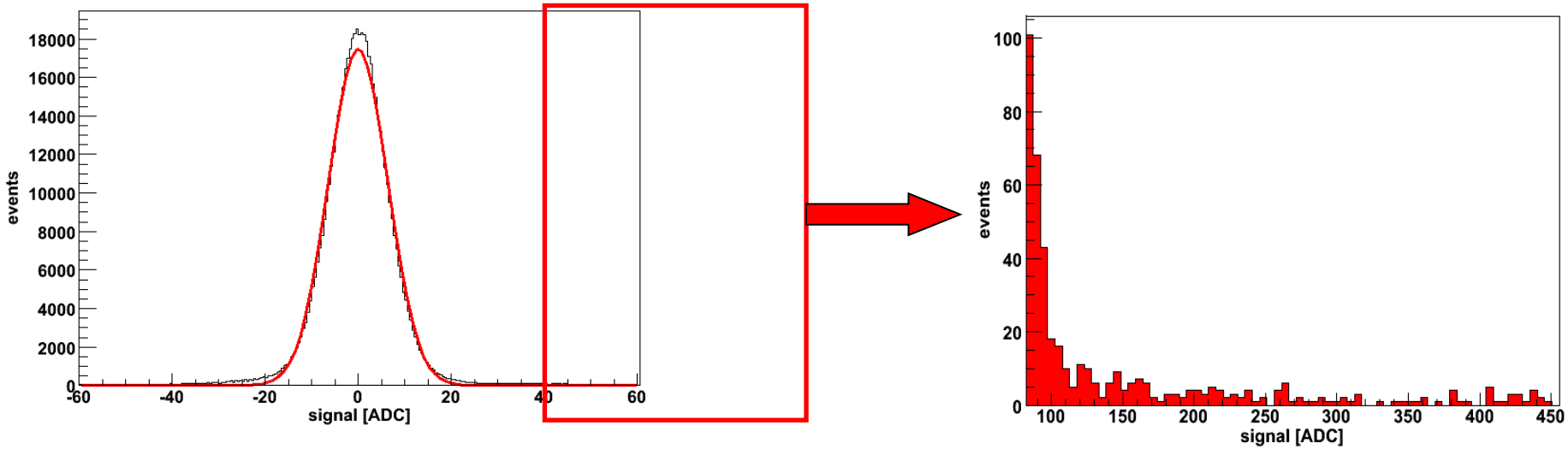
- Signal-to-threshold ratio significantly lower
- Similar behaviour of signal-to-noise and signal-to-threshold ratio



CiS PMS04 noise occupancy results

- Wide non-gaussian tails, probably from micro discharges

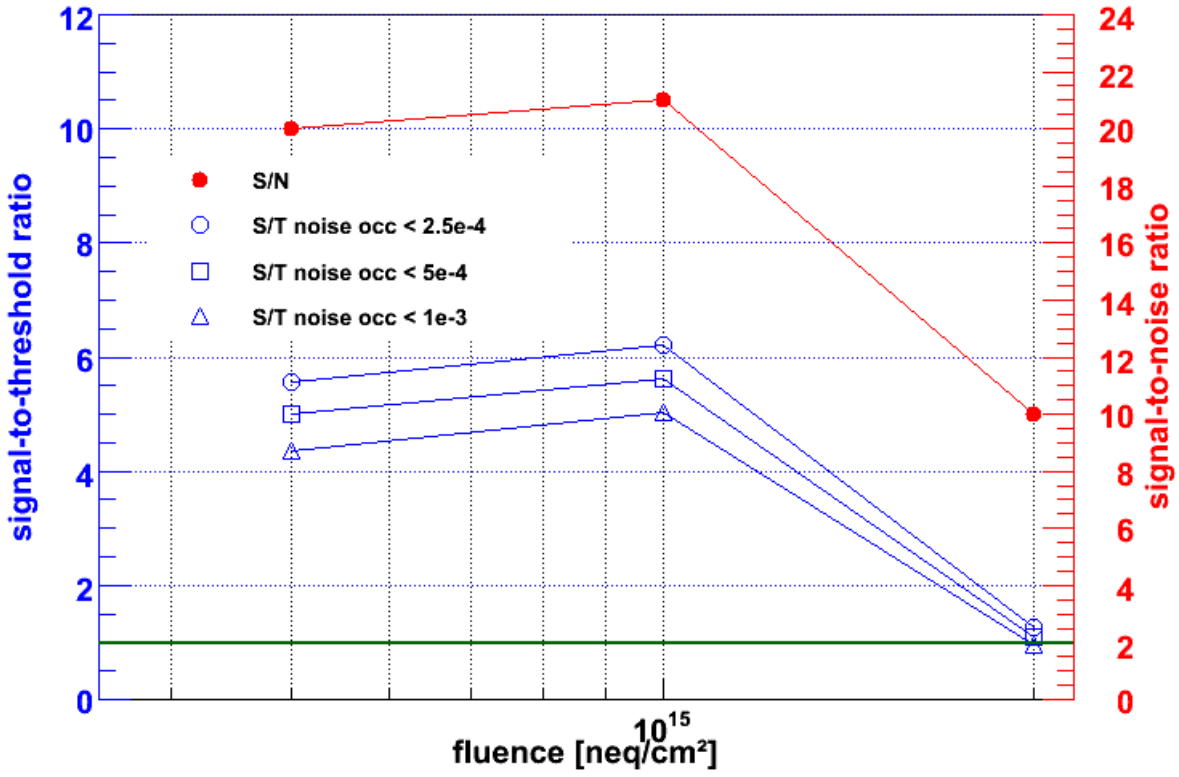
  → High thresholds required to avoid fake hits in binary readout system



CiS PMS04 noise occupancy results

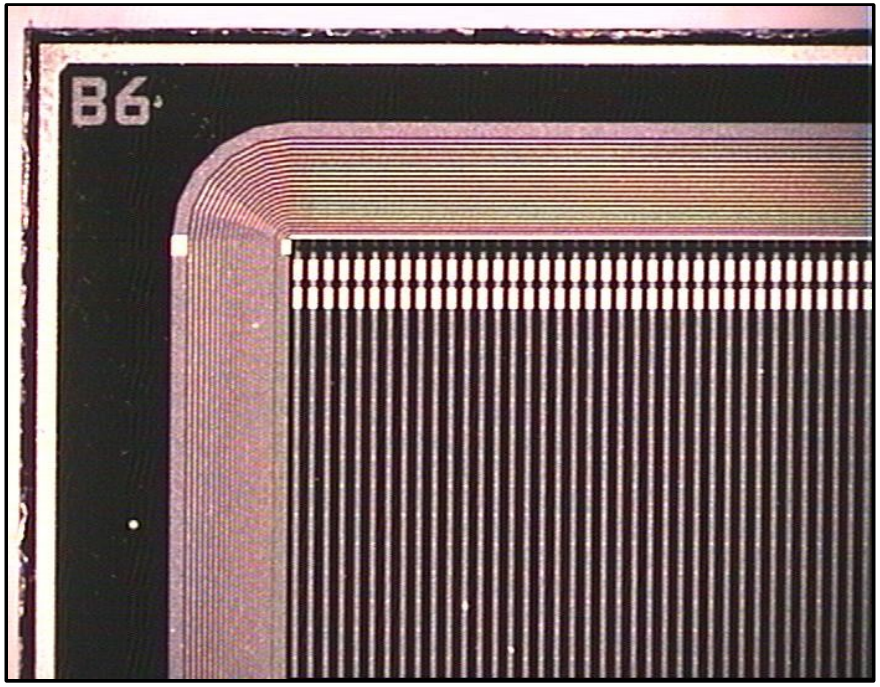
- Signal-to-threshold ratio very low, even < 1 for $\Phi = 2*10^{15}\ n_{eq}/cm^2$

  → Landau MPV below threshold!



CiS MPI expitaxial sensors

- Miniature sensors, approx. 1x1 cm^2
- P-type epitaxial silicon
- Thickness 75 µm
- 96 strips, strip pitch 80 µm
- DC coupling
- Irradiated to
  - $5*10^{14}$ n_{eq}/cm^2
  - $1*10^{15}$ n_{eq}/cm^2
  - $2*10^{15}$ n_{eq}/cm^2



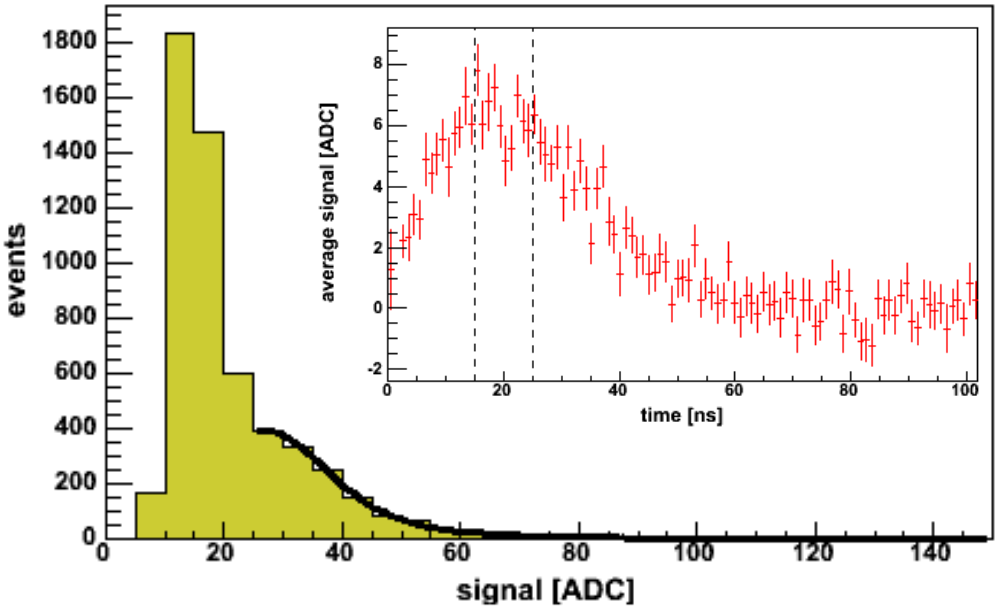
CiS MPI expitaxial sensors

- Charge collection measurements done
- Deposited charge in 75 µm silicon (unirradiated): 5.3 ke^-
- Noise for $\Phi = 5*10^{14}\ n_{eq}/cm^2 \approx$ 1.4 ke^- already

  → low S/N (< 4), signal and noise can't be separated easily

Further analysis required, application of a noise subtraction algorithm provided by MPI Munich,

thanks to Anna Macchiolo & Philipp Weigell



$\Phi = 5*10^{14}\ n_{eq}/cm^2$, 350 V

Conclusion & Outlook

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- Charge collection measurements done with sensors of different thicknesses, materials and fluences
- No signal loss between $5*10^{14}$ n_{eq}/cm^2 and $1*10^{15}$ n_{eq}/cm^2
- For $\Phi > 1*10^{15}$ n_{eq}/cm^2 in both HPK ATLAS07 and CiS PMS04 sensors more charge is collected than expected due to trapping
- If bias voltage is high enough, signal-to-noise ratio at sLHC fluences is sufficient for both HPK and CiS PMS04 sensors
- For binary systems noise occupancy is important, sensors with micro discharges unusable due to numerous outliers

Next steps:

- Further analysis of measurements of CiS MPI epitaxial sensors
- Laser measurements with CiS MPI epitaxials for higher signal

Backup slides

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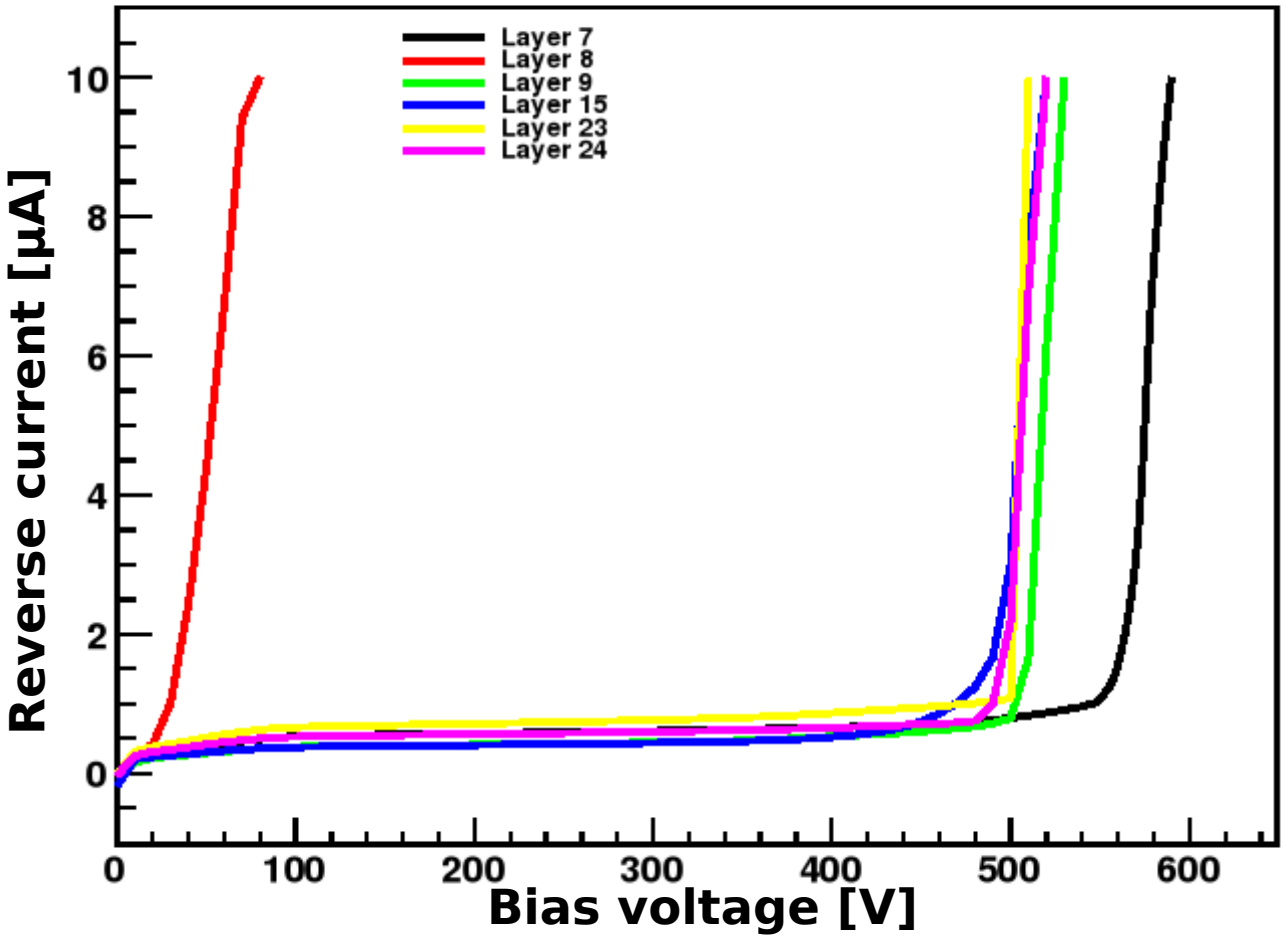
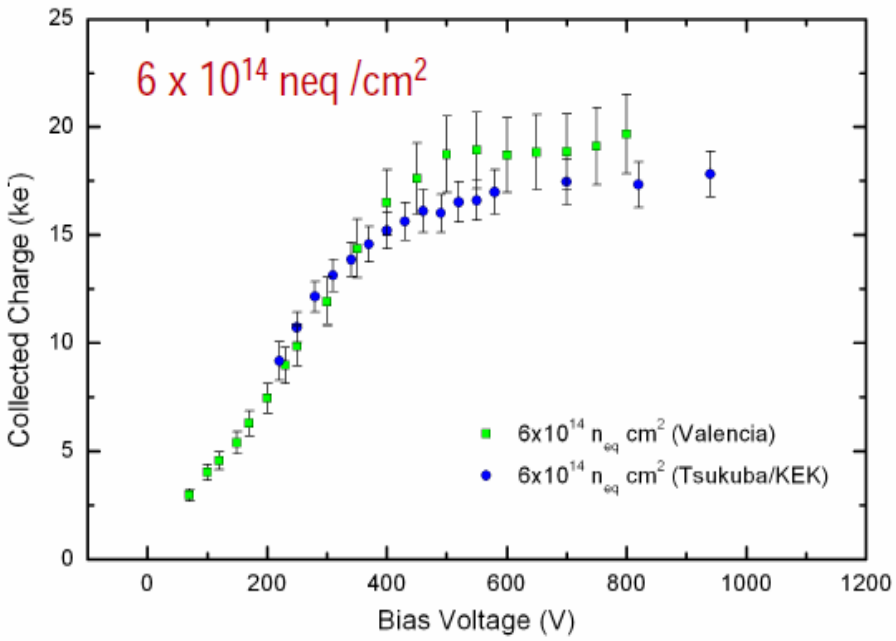
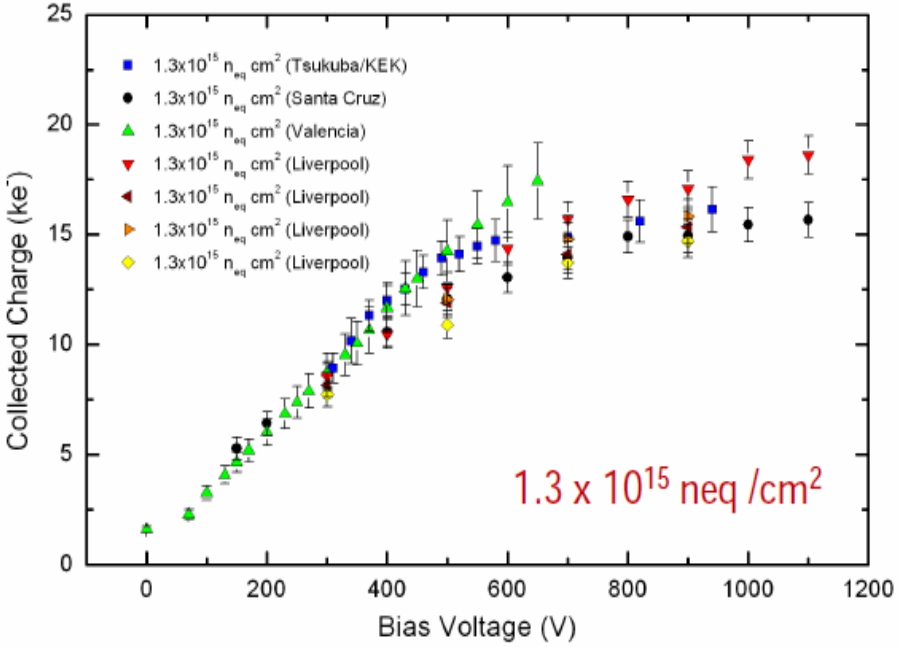
- Backup slides -

CiS PMS04: I-V curves unirradiated



Backup: reference results HPK ATLAS07





Urmila Soldevila (IFIC, Valencia): The ATLAS Tracker Upgrade: Short Strip Detectors for the SLHC (11th ICATPP Conference)

Backup: HPK ATLAS07 sensor properties

Sensor dimension (dicing center-center)	1 cm x 1 cm
Number of strips, Z1-Z5 (Z6)	104 (77)
Strip pitch, Z1-Z5 (Z6) (μm)	74.5 (100)
Strip length (cm)	0.80
Strip width, implant/metal (Z1-Z6), (Z5)	16/22, 22/16
Distance between bias rail and n-strips implants (Z1)/(Z2-Z6)/(Z4) (μm)	12/70/20
Sensor position	Z1:(P7,19) Z2:(P2,5,8,14,17,20), Z3:(P1,3,6,9,13,15,18,21) Z4:(A-P4,B-P10,C-P16,D-P22), Z5: (P11,23), Z6:(P12,14)
Interstrip capacitance (one-neighbor-both) (pF/cm)	~0.80 [7]
Body capacitance per strip (pF/cm)	~0.27 [7]
Bias resistance (Polysilicon) (MΩ)	~1.5
Signal readout	AC coupling
AC coupling breakdown voltage (V)	>100

Y. Unno et al.: Developement of n-on-p Silicon Sensors for very high radiation environment