Comparative Studies of Irradiated 3D Silicon Strip Detectors on p-type and n-type Substrate

Michael Köhler, Michael Breindl, Karl Jakobs, Ulrich Parzefall, Jens Preiss
University of Freiburg

Celeste Fleta, Manuel Lozano, Giulio Pellegrini
IMB-CNM, CSIC (Barcelona)

Richard Bates, Chris Parkes
University of Glasgow

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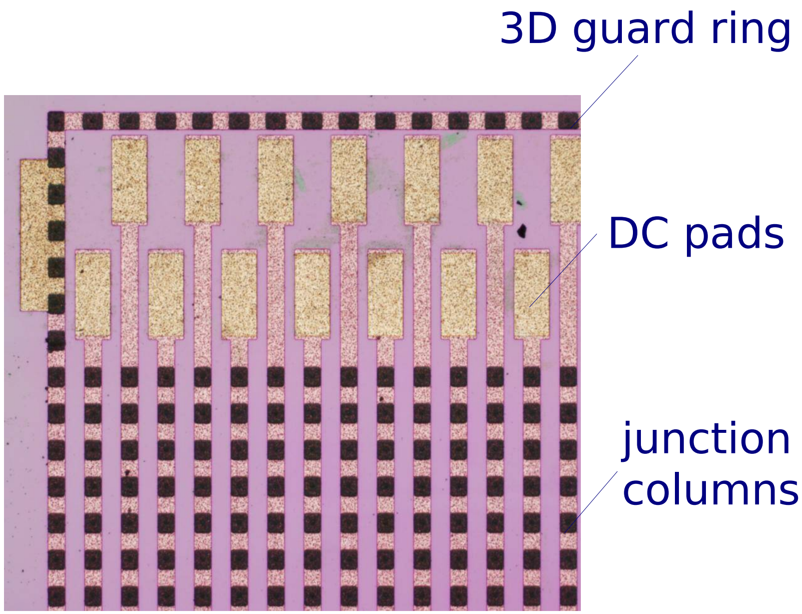
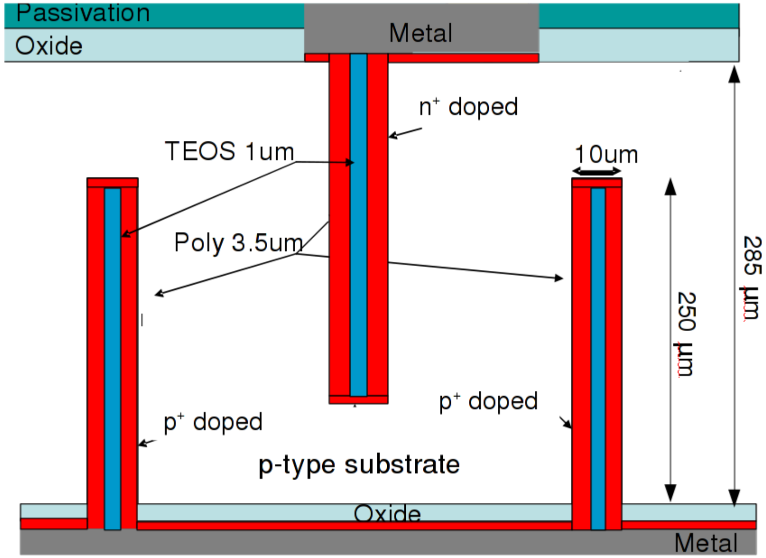
Double-Sided 3D Detectors

- **CNM design:**
  - **285 μm thick p-type or n-type FZ silicon**
  - **250 μm deep junction columns (n^+ or p^+, front side)**
  - **250 μm deep ohmic columns (p^+ or n^+, back side)**

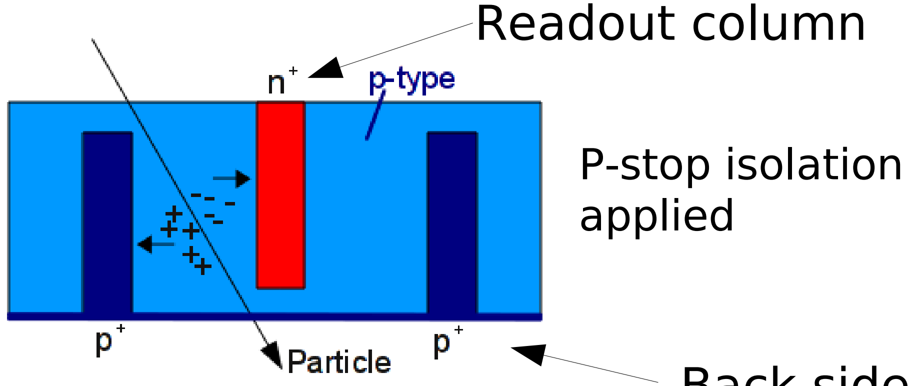




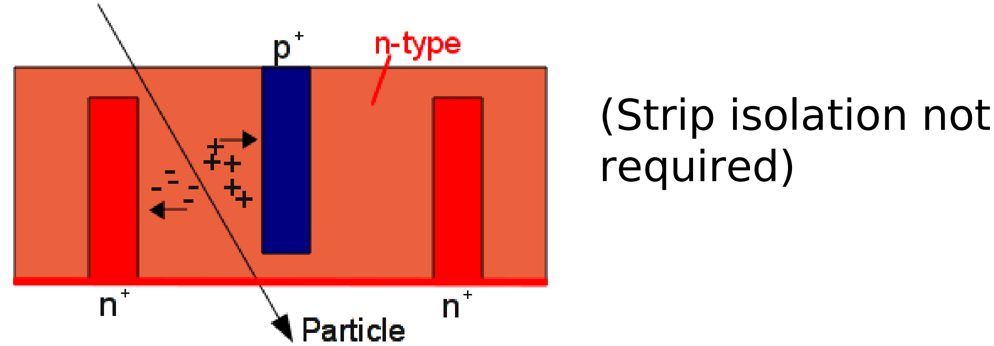
- **Strip detectors: Junction columns connected to strips on front surface**
- **AC-coupling achieved by AC-coupled pitch adapters made by HIP (see talk by Jaakko Härkönen)**

Investigated Detectors

- **P-type (n⁺-in-p):**
  - **unirradiated**
  - **$2x10^{15}$ n_{eq}/cm^2**
  - **$2x10^{16}$ n_{eq}/cm^2**



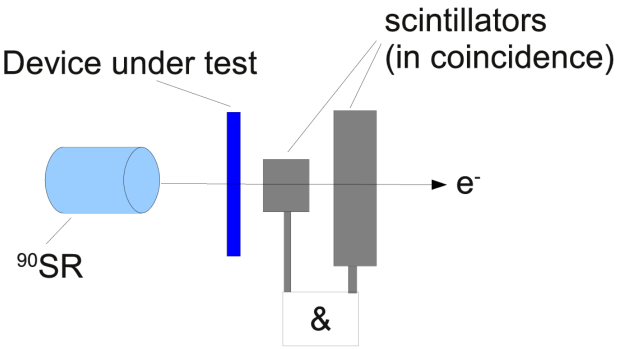
- **N-type (p⁺-in-n):**
  - **unirradiated**
  - **$2x10^{15}$ n_{eq}/cm^2**
  - **$2x10^{16}$ n_{eq}/cm^2**



- **Detectors irradiated at the proton cyclotron Karlsruhe with 25 MeV protons**
- **Annealing state: ~ 5 days at RT (only p-type detector, $2x10^{16}$ n_{eq}/cm^2: ~30 days RT)**
- **Comparison of n-type and p-type detectors**
- **Investigation of charge collection and noise of irradiated detectors at different temperatures**

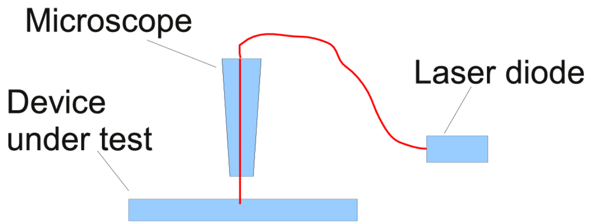
Setups

- **Beta setup:**
  - **Charge collection measurements**
  - **^{90}SR source**



- **Laser setup:**
  - **Space-resolved relative signal**
  - **Motorised x-y stages, Laser scans with 2 µm step size**
  - **IR laser, 974 nm wavelength**

    → Absorption length: ~90µm (in Si, T=-20°C)



- **Cooling:**
  - **Based on liquid nitrogen**

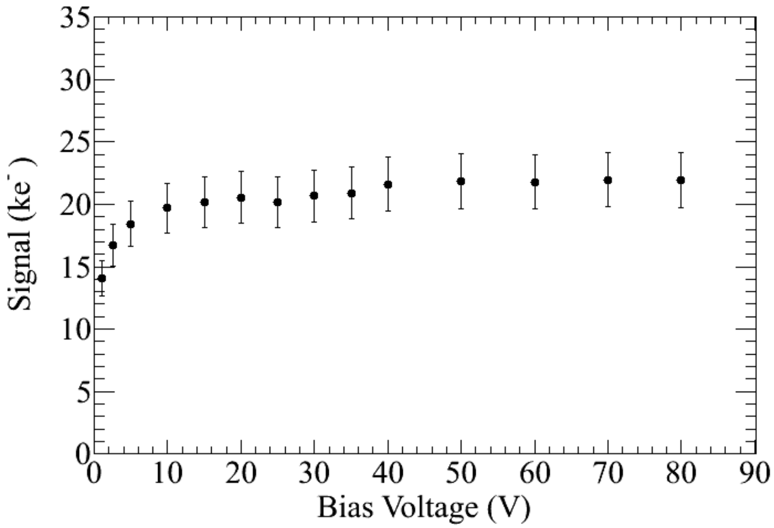
    → Sensor is cooled with evaporated nitrogen
  - **Temperatures down to -60°C achievable**

- **Alibava setup (Beetle chip), temperature dependent calibration performed**

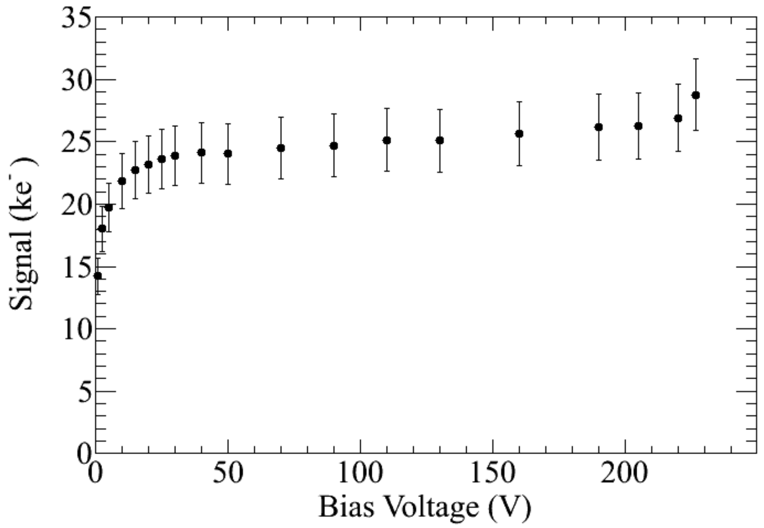
Charge Collection: Unirradiated

- **Charge collection, T = -16°C**
- **Thickness: (285 +- 15) µm → expected signal: (22 +- 1) ke$^-$**

p-type



n-type



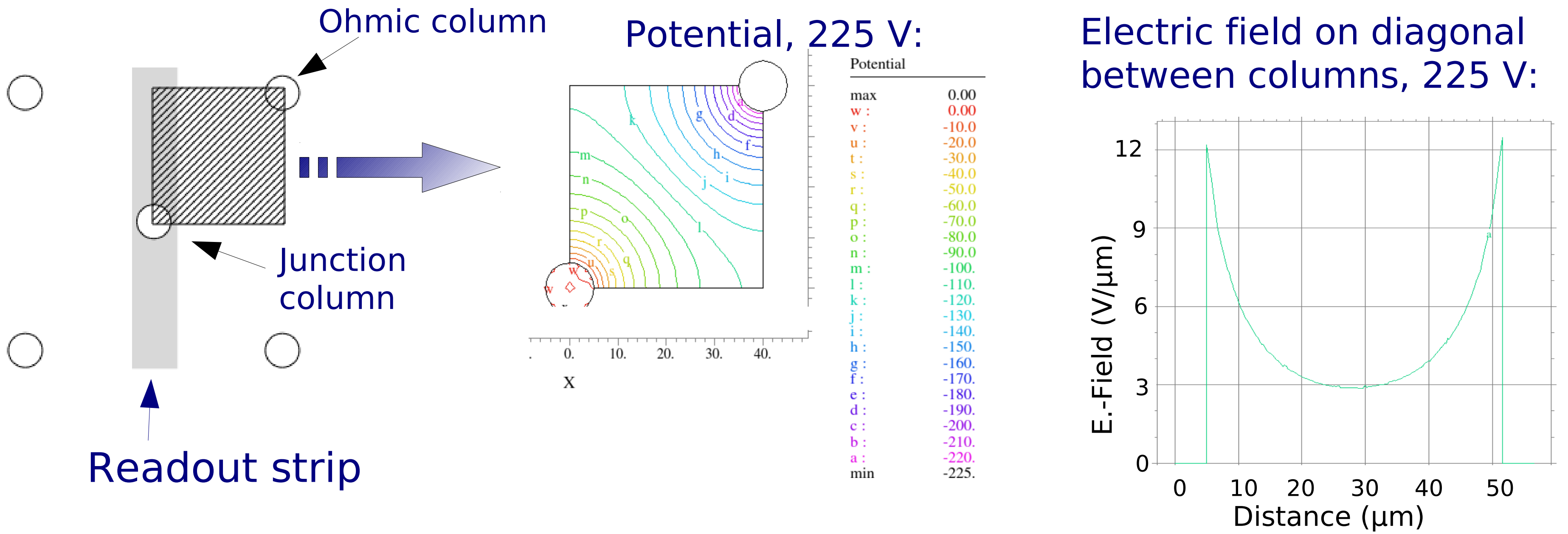
- **Full signal (22 ke$^-$) can be measured**
- **Breakdown at ~80 V**

- **Above 220 V: Signal increasing → Charge multiplication???**
- **Breakdown at ~230 V**

Electric Field Simulations

- **Charge multiplication possible in unirradiated 3D detector?**
- **Simplified field simulations using FlexPDE 5.1.0s**
- **Restrict on simulation of quarter unit cell of 3D detector**

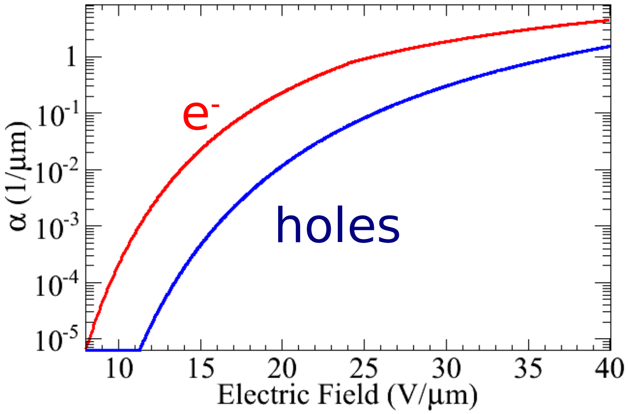
→ In reality: field distortions due to further columns, but this gives a rough idea...



- **Maximum electric field: ~ 12 V/µm → multiplication could be possible**
  - **Real fields might be even higher e.g. at column tips**

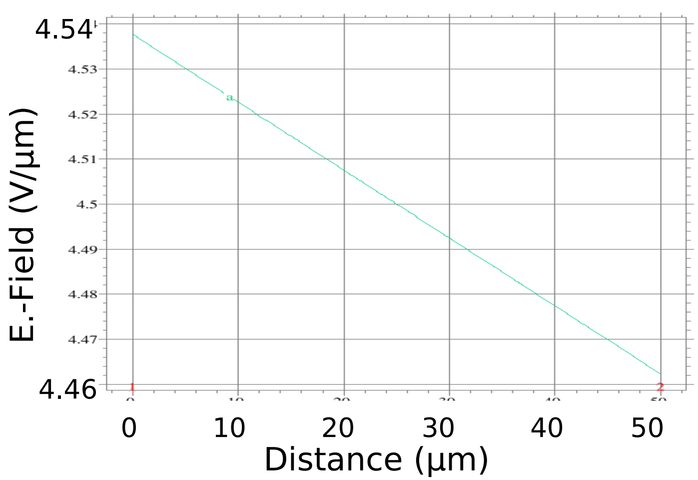
Impact Ionisation

- **Ionisation rates (= number of e-h paris generated per distance):**



- **Data of W. N. Grant, 1973 (T= -20 °C)**
- **Multiplication expected for Fields higher than 10 V/µm**

- **Comparison: E.-field in planar pad detector of 50 µm thickness, 225 V**

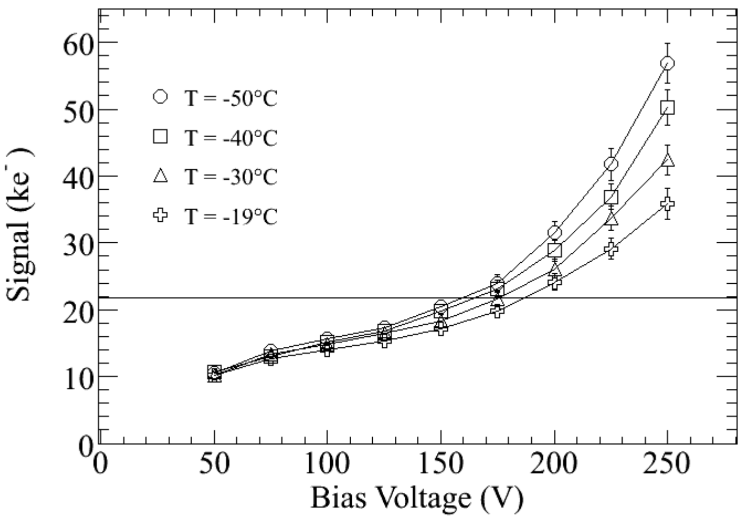


- **Max. E.-field: ~4.5 V/µm**
- **Although same spacing between electrodes as in 3D detector: fields not high enough for multiplication**

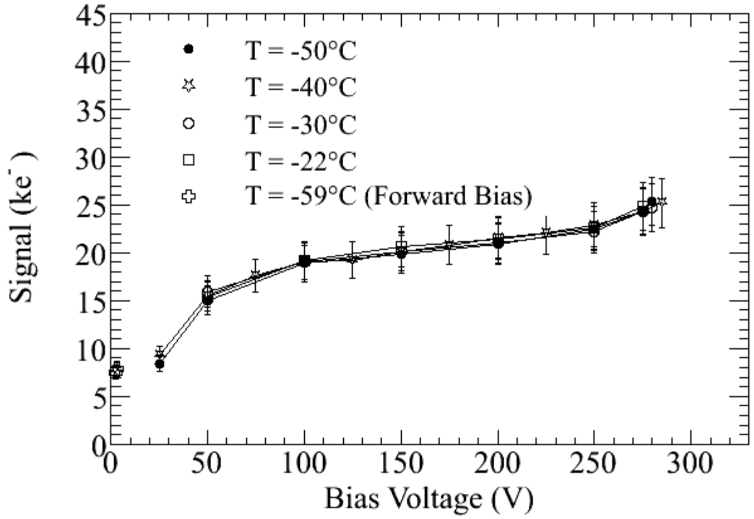
Charge Collection: $2x10^{15}\, n_{eq}/cm^2$

- **p-type vs n-type, diff. temperatures (temperature dependent gain calibration used)**

p-type



n-type



- **Charge multiplication above 150 V**
- **Lower temperatures: higher charge multiplication**

- **Charge multiplication above 260 V?**
- **No temperature dependence**
- **Higher plateau compared to p-type sensor**
- **Reverse bias: Full signal measured**
- **Forward bias: 6.5 ke⁻ at 3 V**

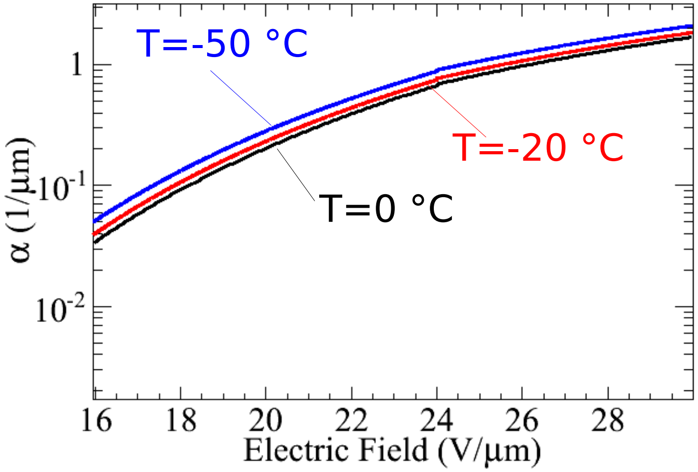
Temperature Dependence of Signal

- **Higher trapping at lower temperature**
  - **For electrons: $\beta_e(T)=\beta_e(T_0)\,(T/T_0)^{-0.86}$ (→ PhD thesis G. Kramberger)**

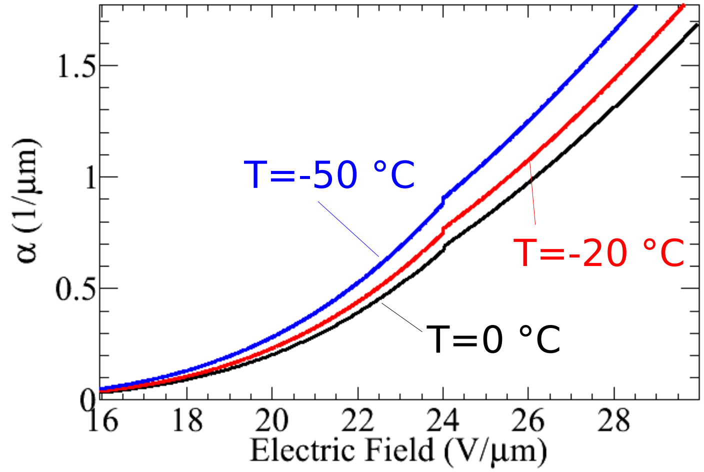
→ **If trapping dominates: slightly lower signal at lower temperature**

- **Ionisation rates of electrons for different temperatures:**

Log. plot



Linear plot

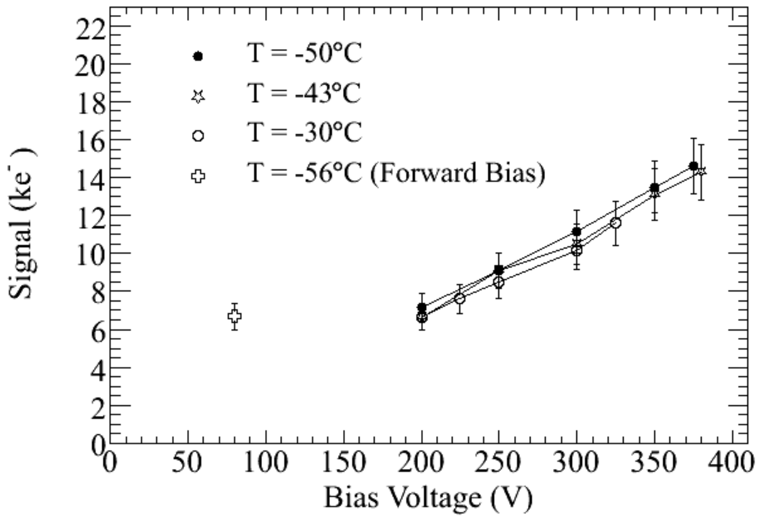


[Parameterisation: W. N. Grant, Solid-State Electronics, Vol. 16, 1973]

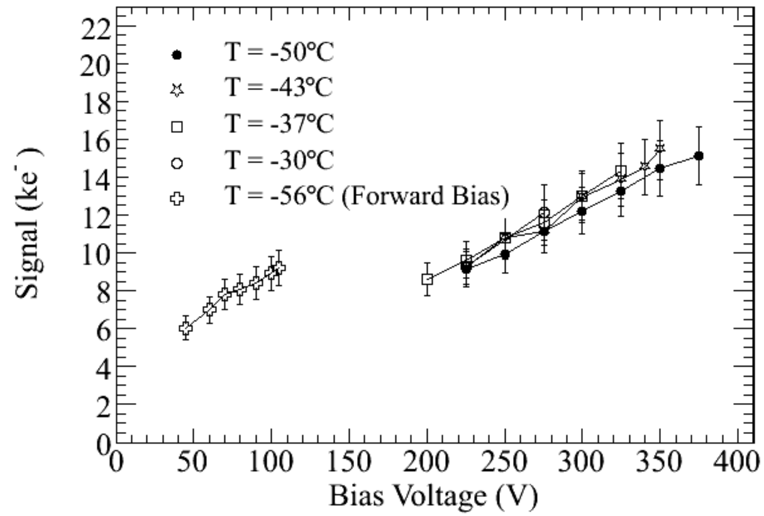
→ **If charge multiplication dominates: higher signal at lower temperature**

Charge Collection: $2x10^{16}\ n_{eq}/cm^2$

p-type



n-type



- **Forward bias: 7 ke⁻ at 80 V**
- **Reverse bias: 15 ke⁻ at 380 V**

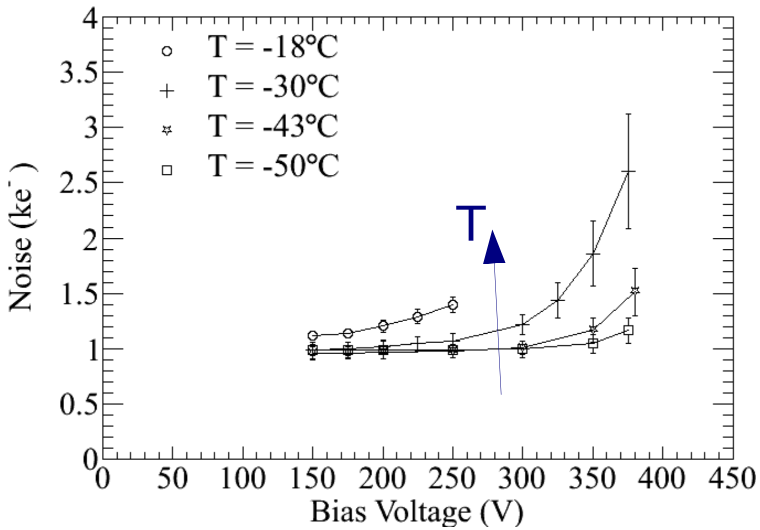
- **Forward bias: 9 ke⁻ at 110 V**
- **Reverse bias: 15 ke⁻ at 350 V**

- **Maximum signal in n^+-in-p and p^+-in-n detector equal!**
  - **In contrast to planar detectors: high weighting field around readout electrode and ohmic electrode**

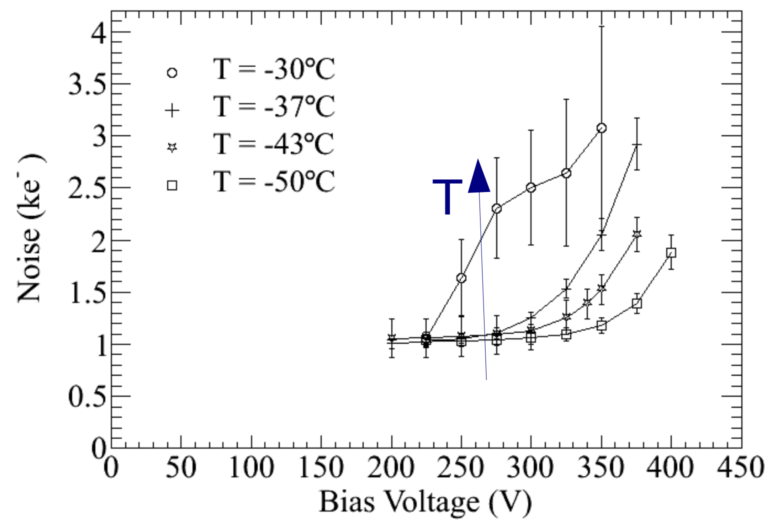
    → Both substrate types behave similar, even after type inversion
- **No significant temperature dependence**

Noise: $2x10^{16}\ n_{eq}/cm^2$

p-type



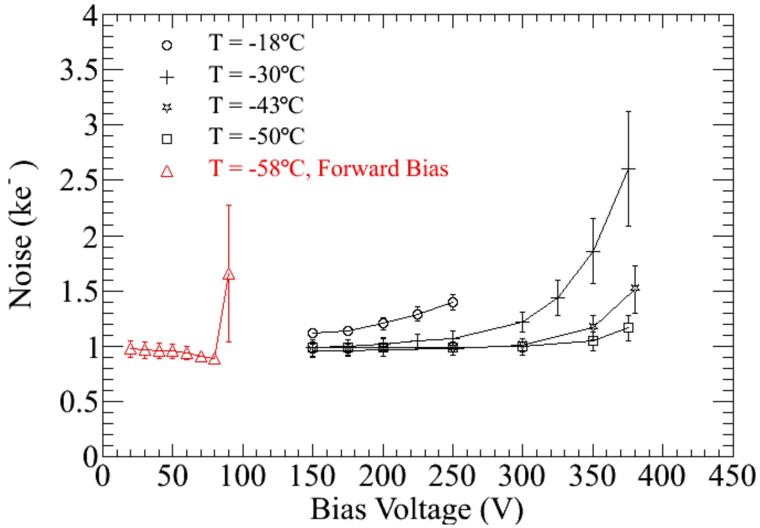
n-type



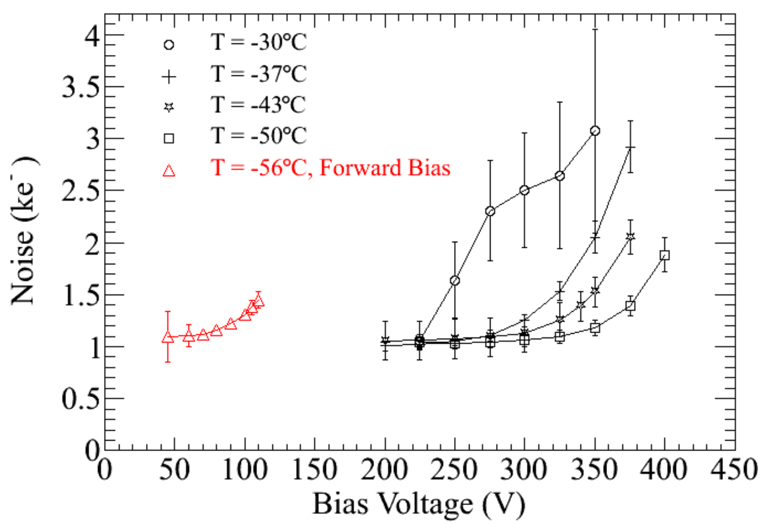
- **Strong noise increase with temperature – stronger than expected by standard shot noise parameterisation**
  - **Lower temperature improves signal-to-noise ratio strongly!**

Noise: $2x10^{16}\ n_{eq}/cm^2$

p-type



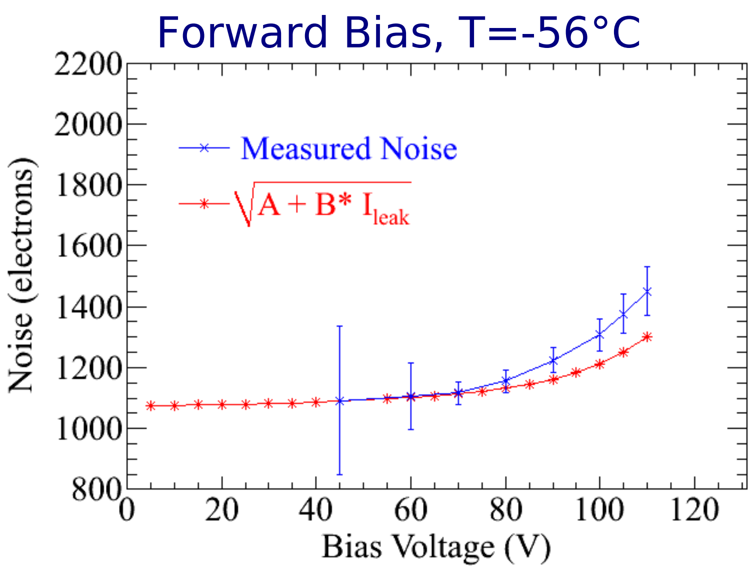
n-type

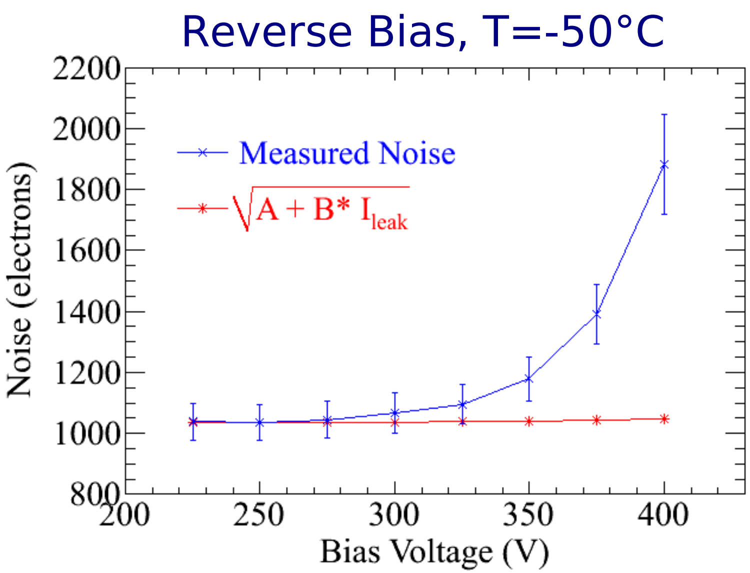


- **Strong noise increase with temperature – stronger than expected by standard shot noise parameterisation**
- **Forward bias:**
  - **Strange behaviour in p-type detector (noise decreasing with increasing bias)**
  - **Higher current, but lower noise than in reverse bias mode**

Noise: n-type, $2x10^{16}$ n_{eq}/cm^2

- **Comparison of measured noise and calculated noise (using shot noise parameterisation)**
  - **Shot noise: sqrt(B*I_{leak}) with I_{leak} in nA; B=220 for Beetle chip with V_{fs}=1000 mV**



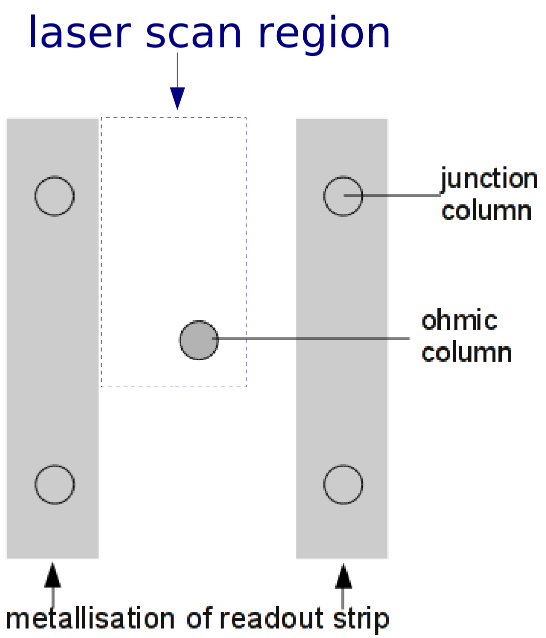


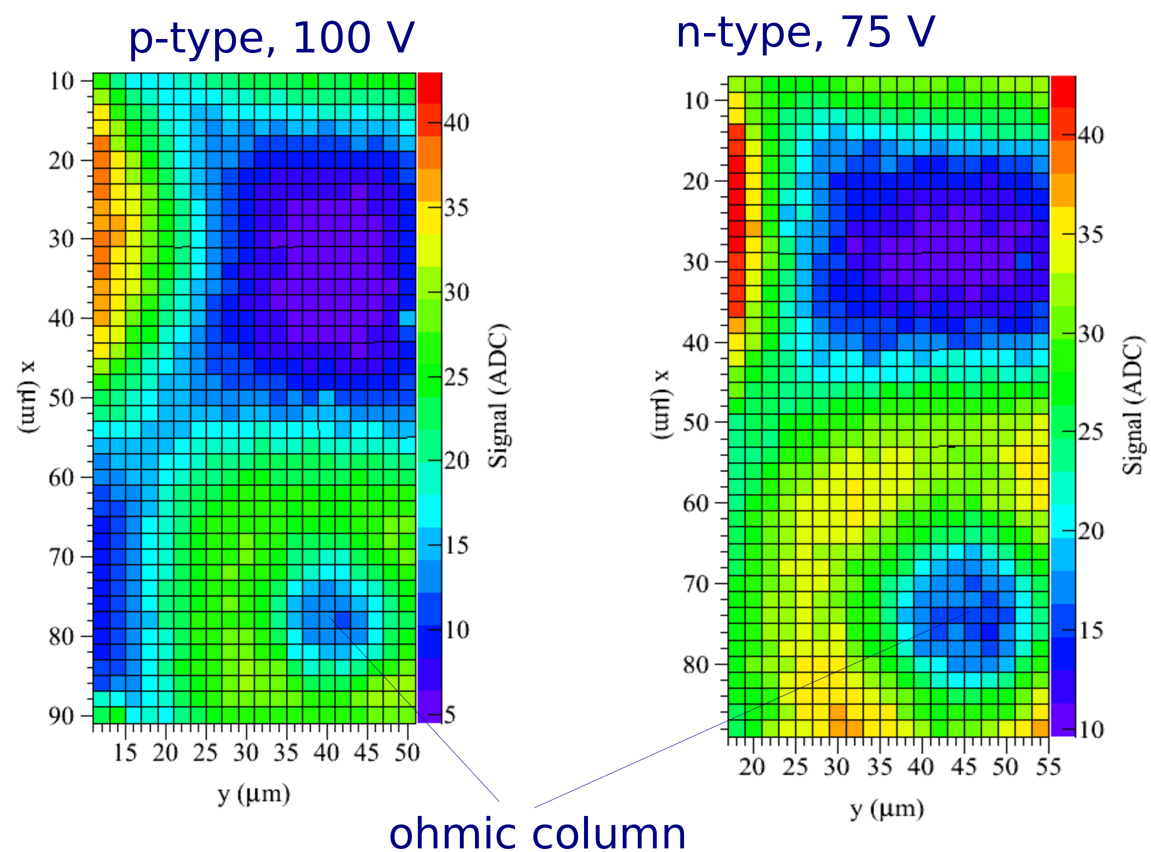
- **Measurement and standard modelling almost agree for forward bias, but not for reverse bias**

  → Reverse bias: Excess noise (typical for charge multiplication)

Laser Scan: $2x10^{16}$ n_{eq}/cm^2 , Low Voltage

- **Space-resolved signal measurement (signal sum of adjacent channels)**





- **Not fully depleted**
- **Active region around junction column and ohmic column**

  → **Double junction**

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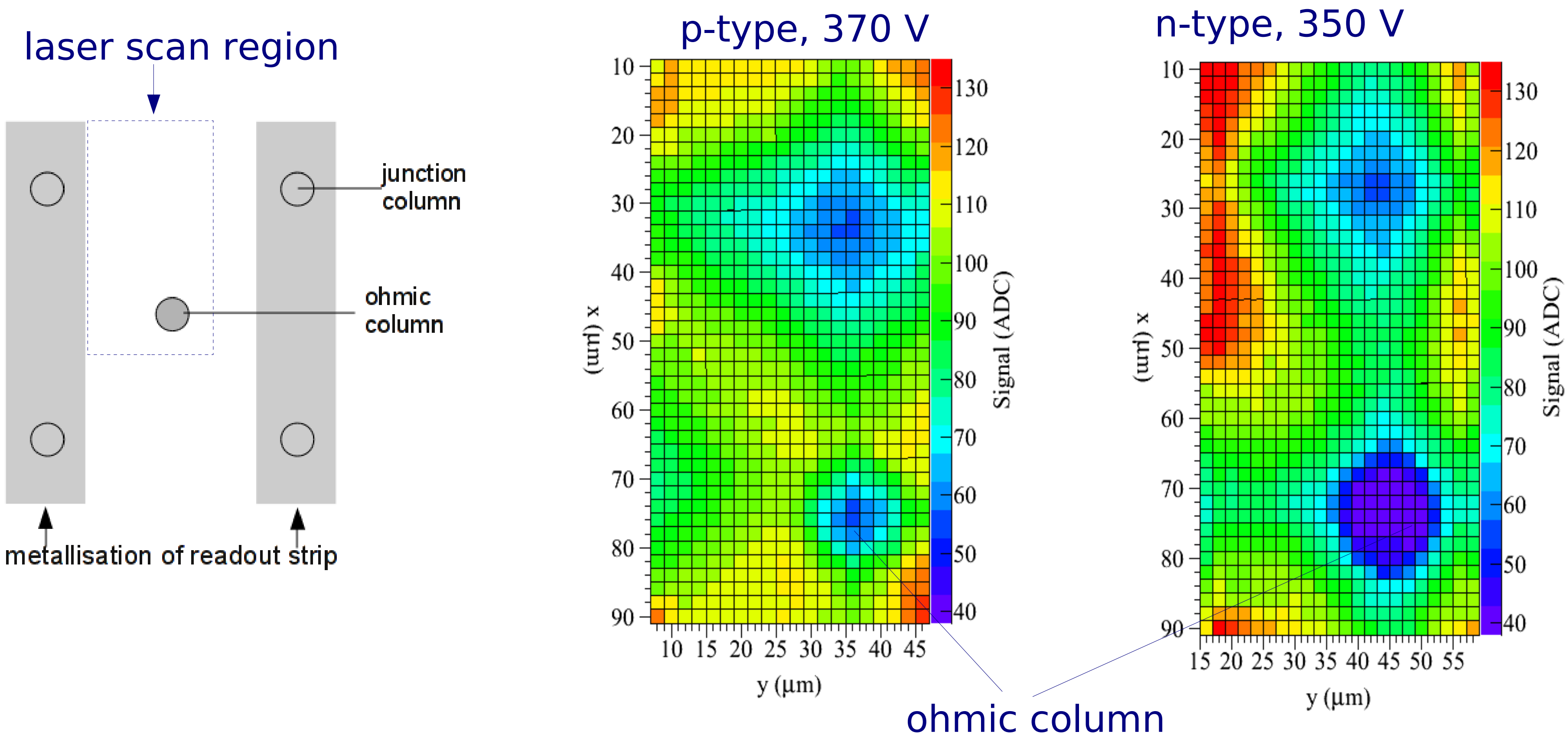
Laser Scan: $2x10^{16}\ n_{eq}/cm^2$, High Voltage

- **Space-resolved signal measurement (signal sum of adjacent signals)**



- **Low field region remains even at highest voltages**
- **N-type detectors: 50% larger column diameter visible**

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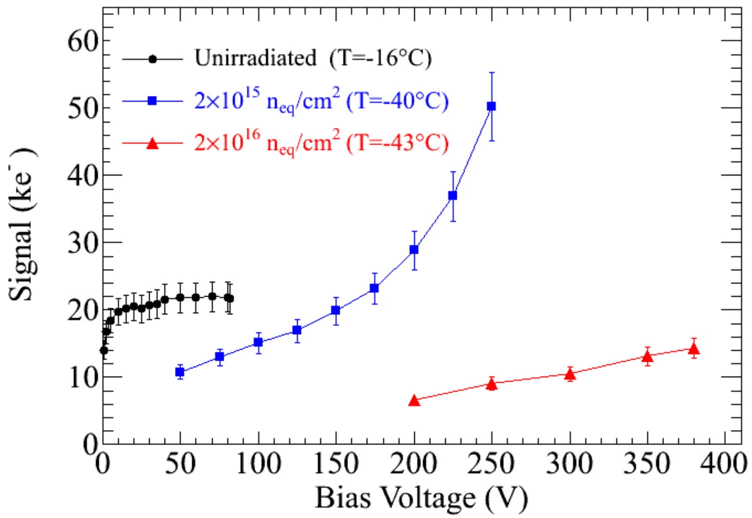
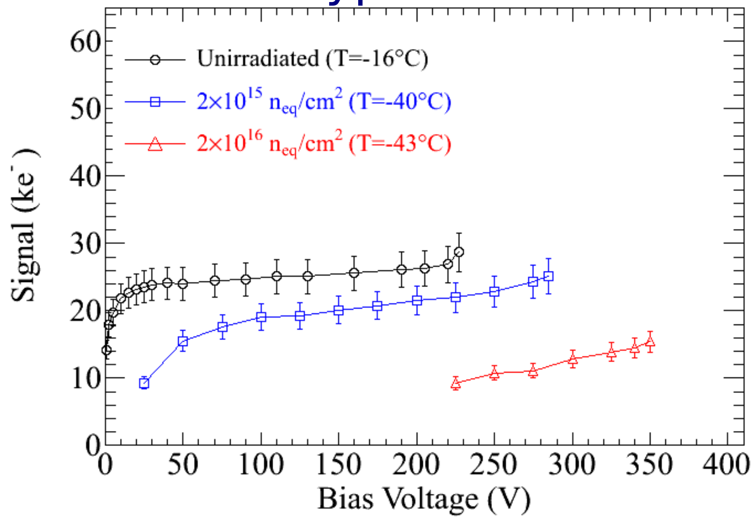
Summary

- **Charge multiplication in unirradiated n-type detector?**
- **Temperature dependence of signal and noise**
- **After fluence of 2×10^{16} n_{eq}/cm^2: no significant difference between n^+-in-p and p^+-in-n detectors**
  - **Maximum signal: 15 ke^- (~70% relative CCE)**
    (NB: no p-stop or p-spray necessary for p^+-in-n detectors → cheaper)

p-type



n-type



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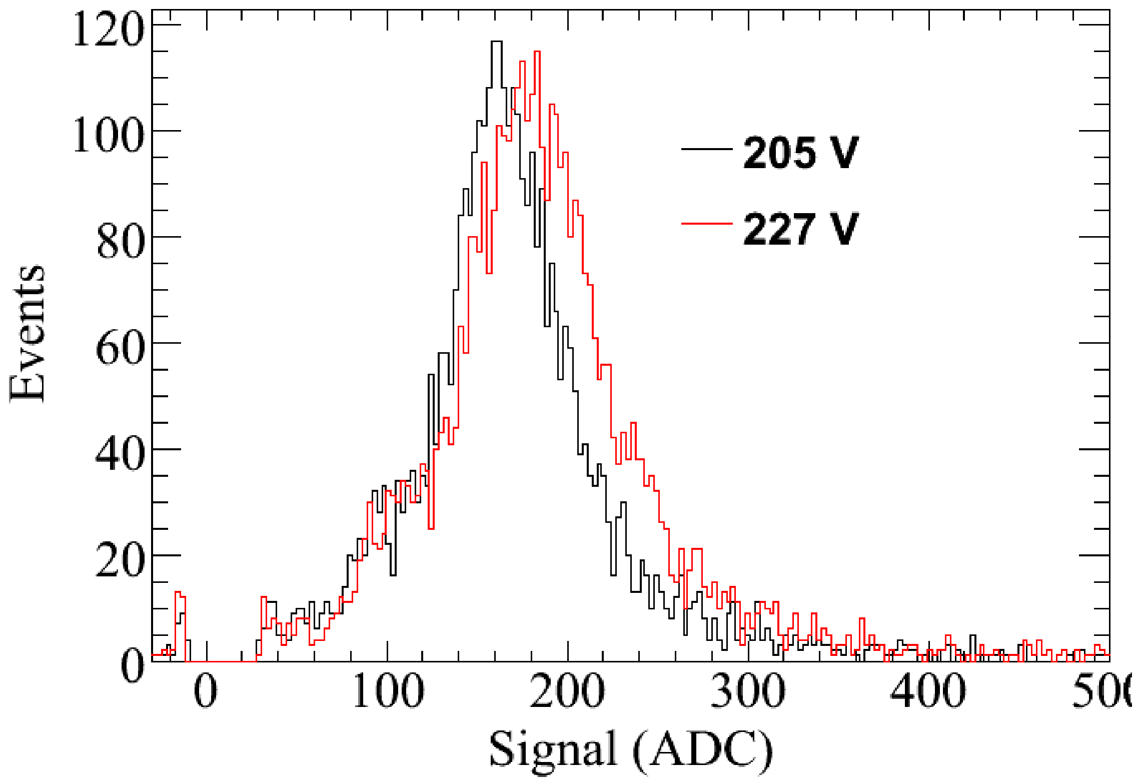
Backup Slides

Unirradiated, n-type: Signal Spectra

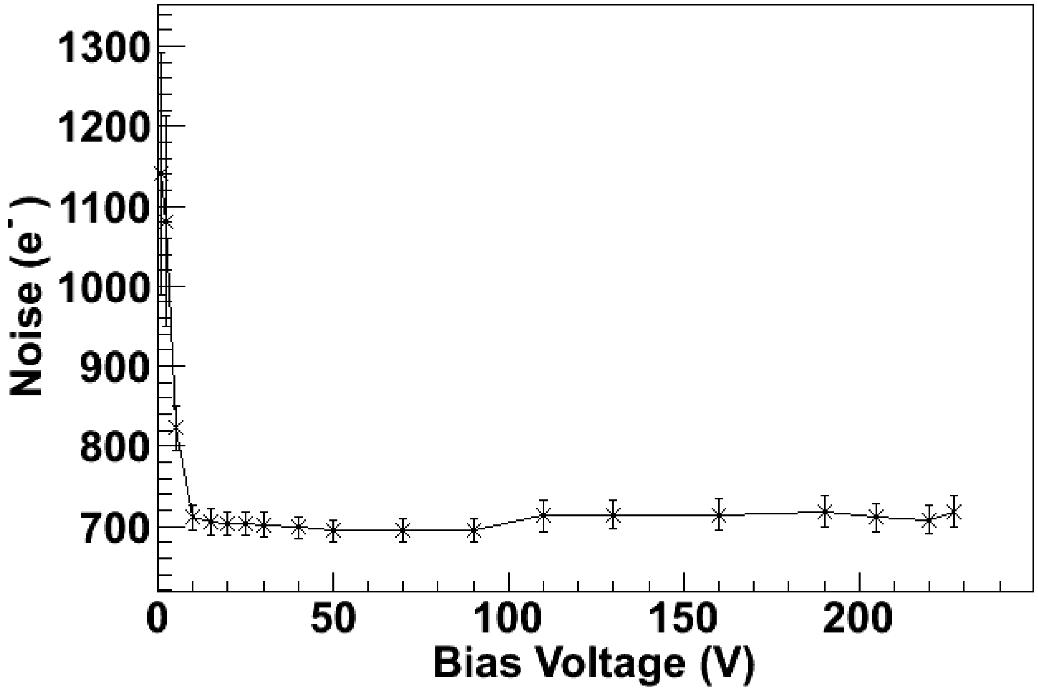
- Comparison of spectra at 205 V and 227 V (T=-17 °C)



- At 227 V: visibly higher MPV, spectrum appears somewhat broader
  → Evidence of charge multiplication?

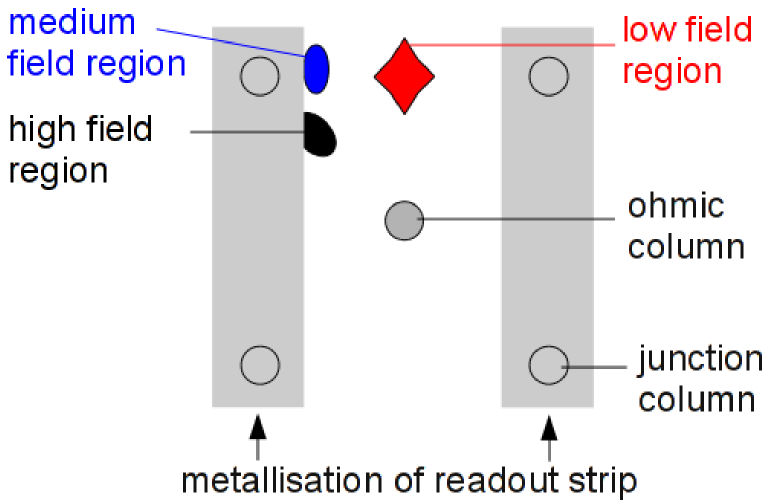
Unirradiated, n-type: Noise vs Voltage

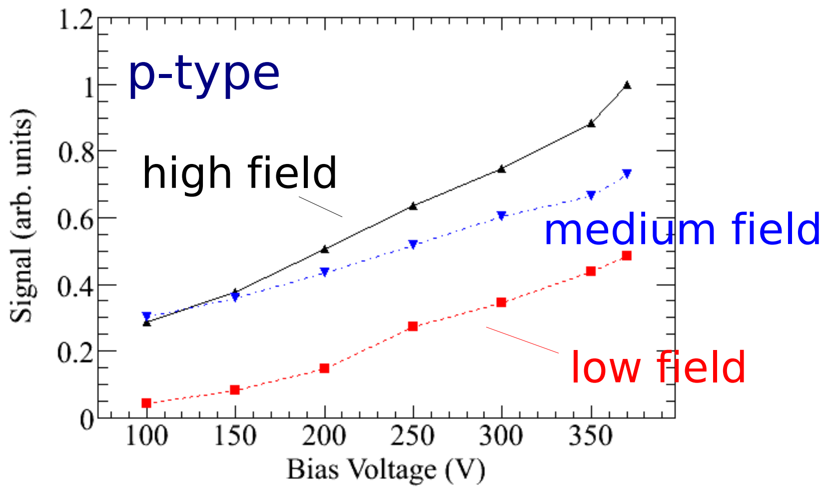
- RMS noise, T = -17 °C
- Above 10 V (= depletion): noise is constant → no noise increase around 225 V, where strong signal increase is measured

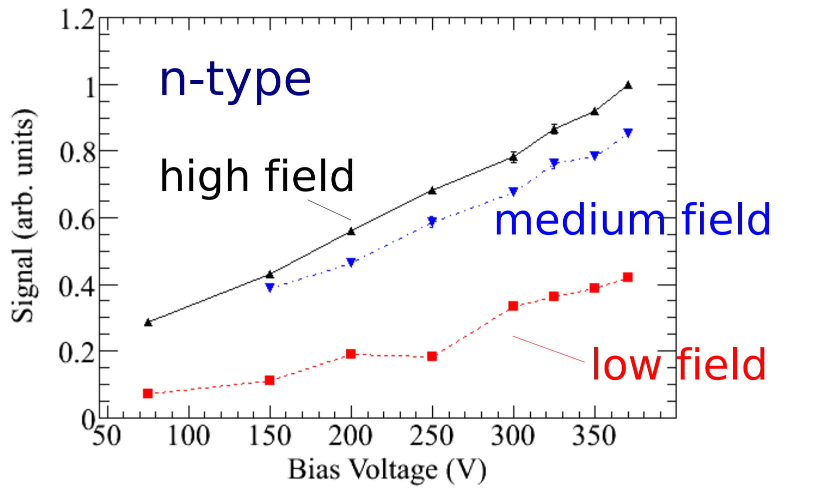


Laser: High Field vs. Low Field, $2x10^{16}\ n_{eq}/cm^2$

- **Laser signals in different regions**







- **Signals normalised to highest signal**
  - **Only relative signals of laser measurements can be compared**
- **Results are similar for p-type and n-type**
  - **Low field region somewhat more expressed in n-type detector**