Comparative Measurements of Irradiated 3D Silicon Strip Detectors with p- and n-Side Readout

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

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

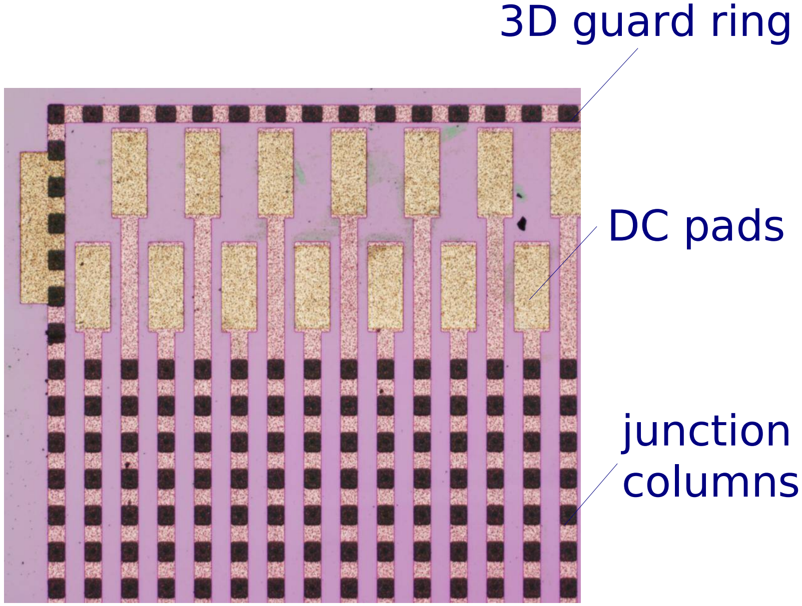
Richard Bates, Chris Parkes
University of Glasgow

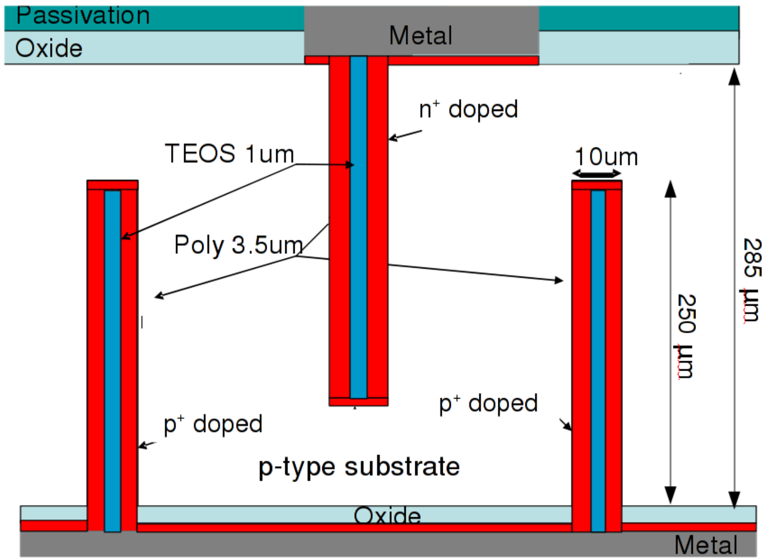
UNI FREIBURG

Thanks to W. de Boer and A. Dierlamm from the Karlsruhe Institute of Technology for the device irradiation!

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)**

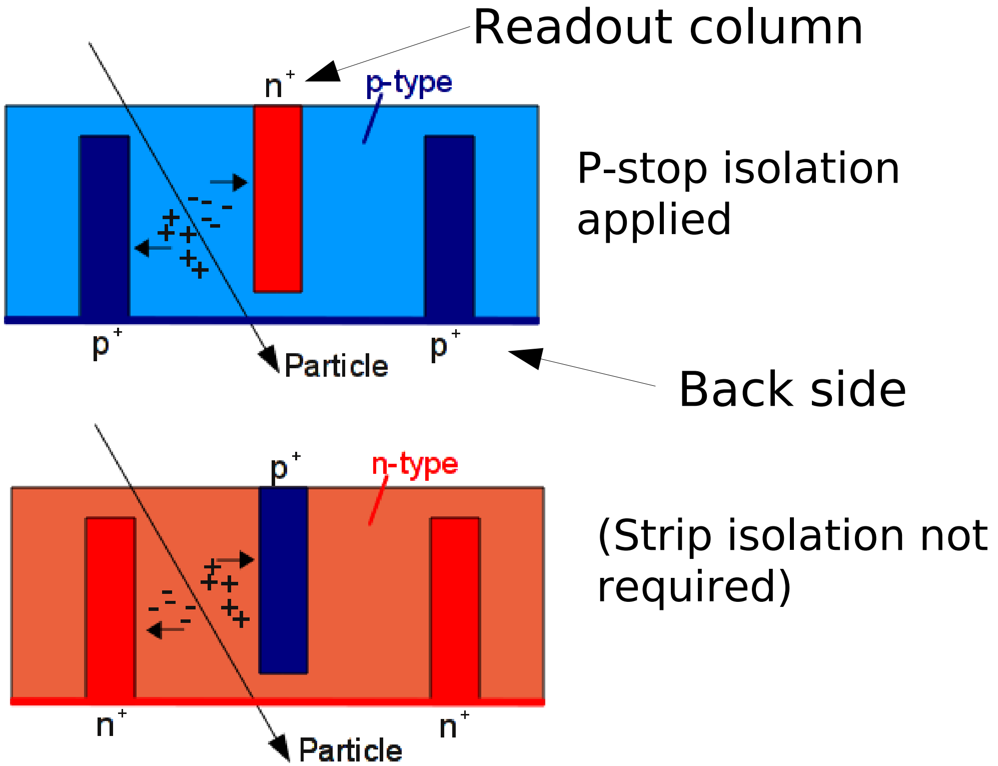




- **Strip detectors: Junction columns connected to strips on front surface**
- **AC-coupling achieved by AC-coupled pitch adapters made by HIP**

Investigated Detectors

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

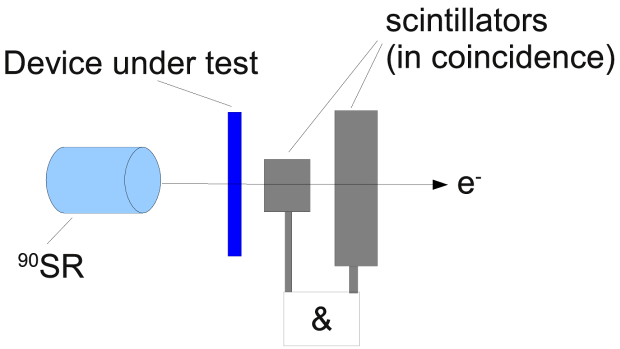


- **N-type (p-in-n):**
  - **unirradiated**
  - **$2x10^{15}$ n_{eq}/cm^2**
  - **$2x10^{16}$ n_{eq}/cm^2**

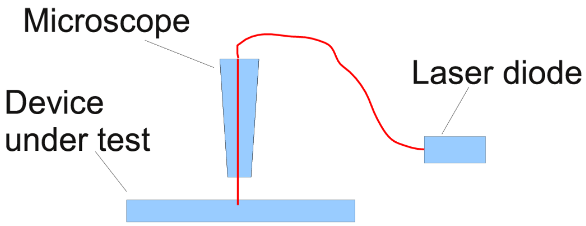
- **Detectors irradiated at the proton cyclotron Karlsruhe with 25 MeV protons**
- **Annealing state: ~ 5 days at RT (only p-type detector, $2x10^{16}$ n_{eq}/cm^2: ~30 days RT)**
- **Comparison of n-type and p-type detectors**
- **Investigation of charge collection and noise of irradiated detectors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



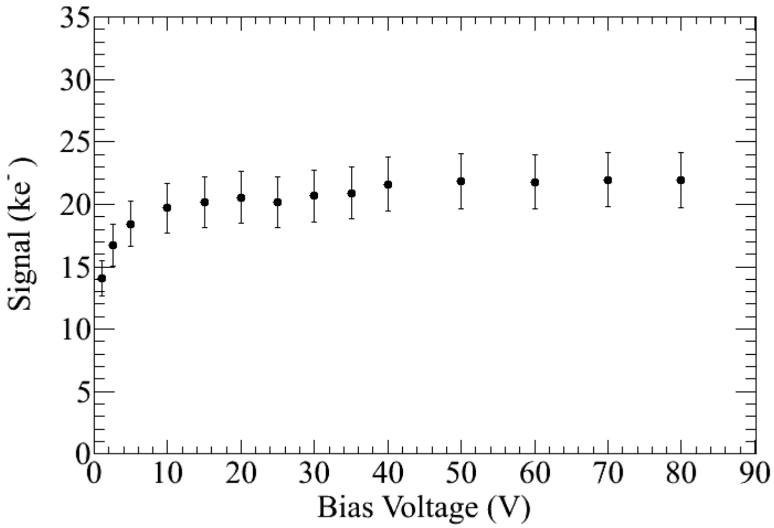
- **Cooling:**
  - **Based on liquid nitrogen**
    - **→ Sensor is cooled with evaporated nitrogen**
  - **Temperatures down to -60°C achievable**

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

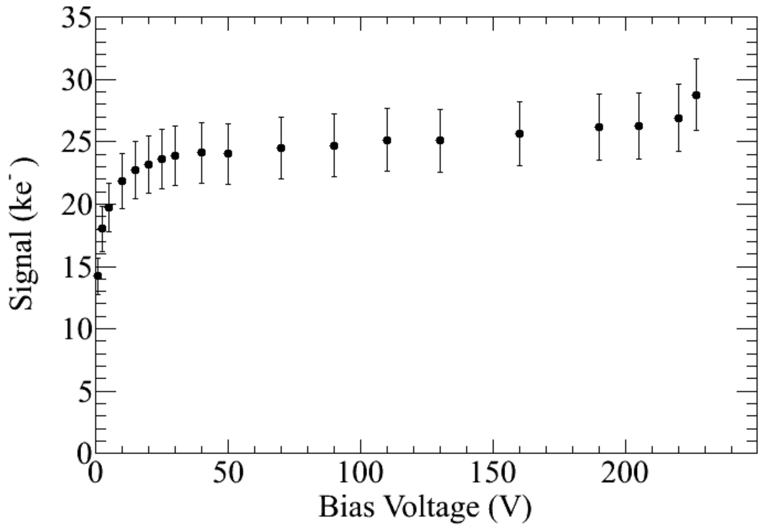
Charge Collection: Unirradiated

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

p-type (n-in-p)



n-type (p-in-n)



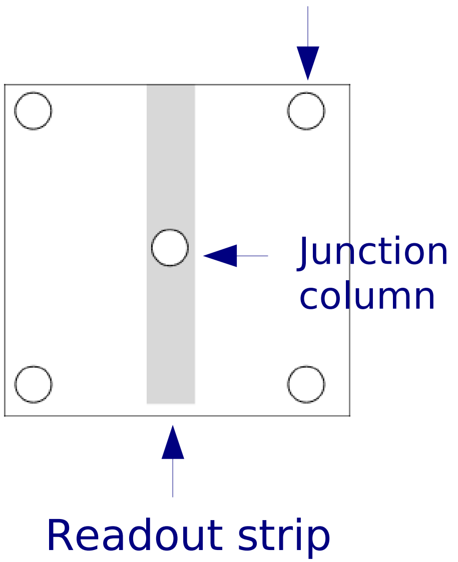
- **Full signal (22 ke^-) can be measured**
- **Breakdown at ~80 V**

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

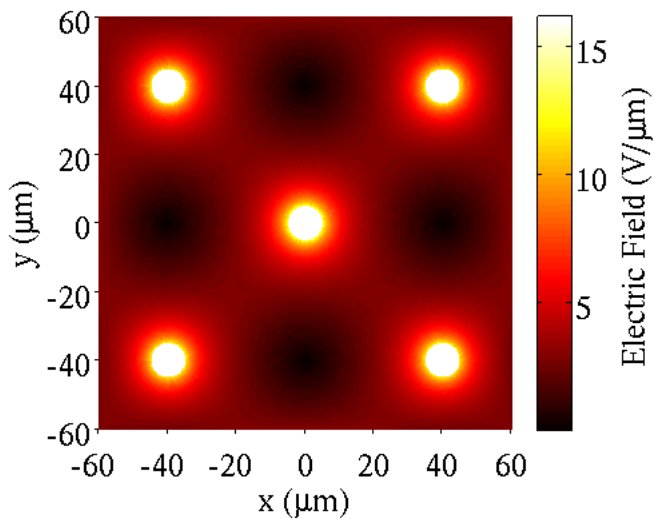
UNI FREIBURG

Electric Field Simulations

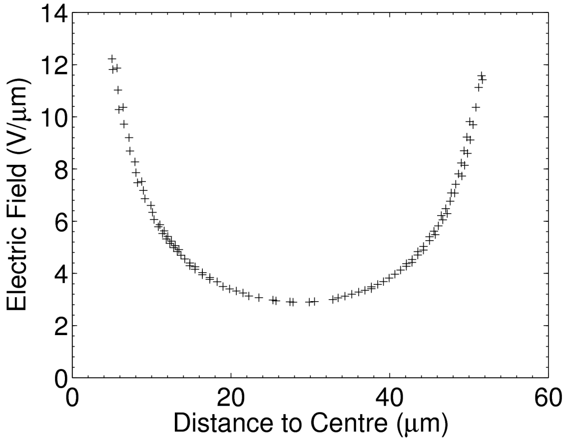
- **Charge multiplication possible in unirradiated 3D detector?**
- **Simulation of electric field (bias voltage V=225 V)**



Electric field, 225 V:



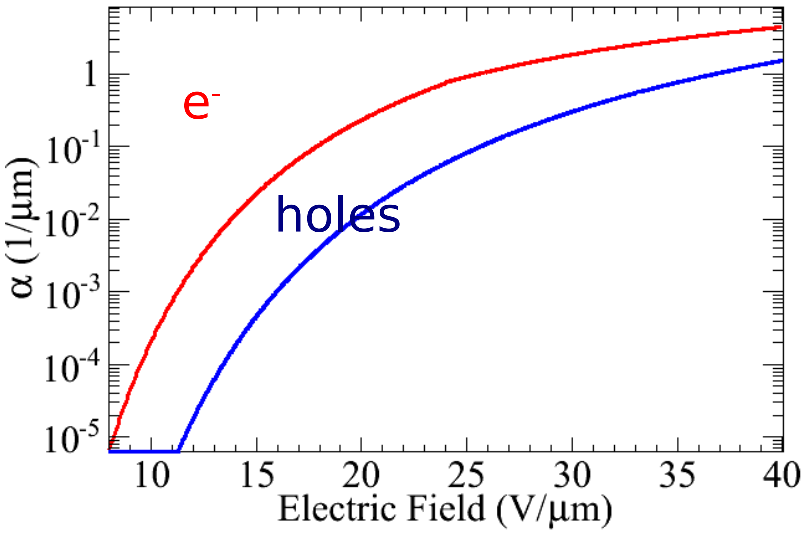
Electric field on diagonal between columns, 225 V:



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

Impact Ionisation

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

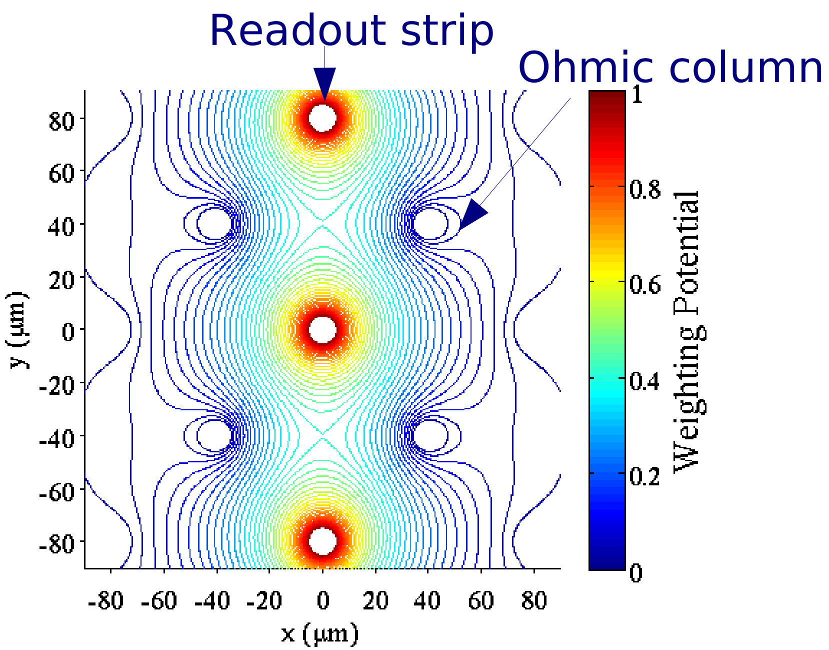


[Parameterisation of W. N. Grant, 1973 (T= -20 °C)]

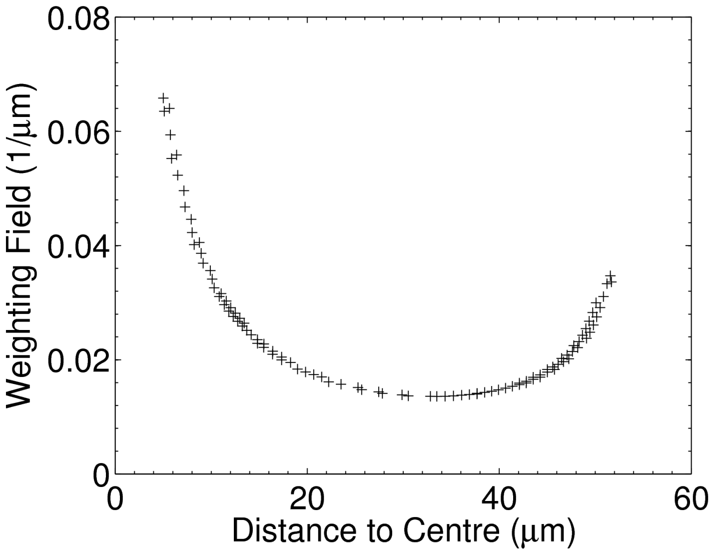
- **Multiplication of electrons expected for fields higher than ~10 V/µm**
- **E-Field in unirradiated p-in-n 3D detector: E_{max} =12 V/µm**
  - **Charge multiplication possible in unirradiated p-in-n detector**

Weighting Field Simulations

- **Weighting Potential concerning central readout strip:**



- **Weighting Field on direct line between junction column and ohmic column:**



- **Weighting Field: peak at junction column and ohmic column**

  → **Electrons and holes contribute to the signal in comparable amount**

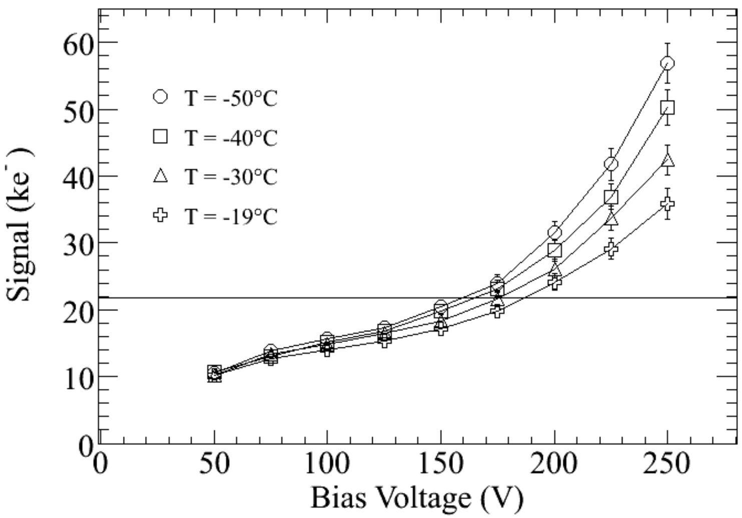
  → **Multiplication of electrons at ohmic columns in p-in-n detectors can increase the signal**

  → **p-in-n and n-in-p behave similarly**

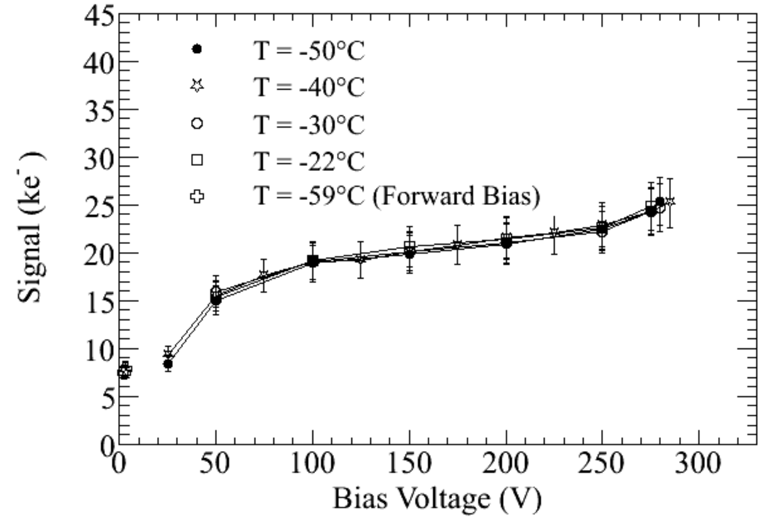
Charge Collection: $2x10^{15}\, n_{eq}/cm^2$

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

n-in-p



p-in-n

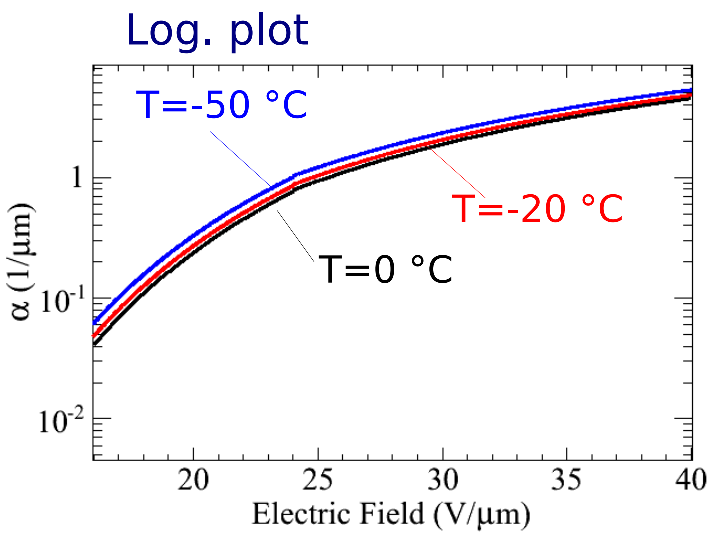


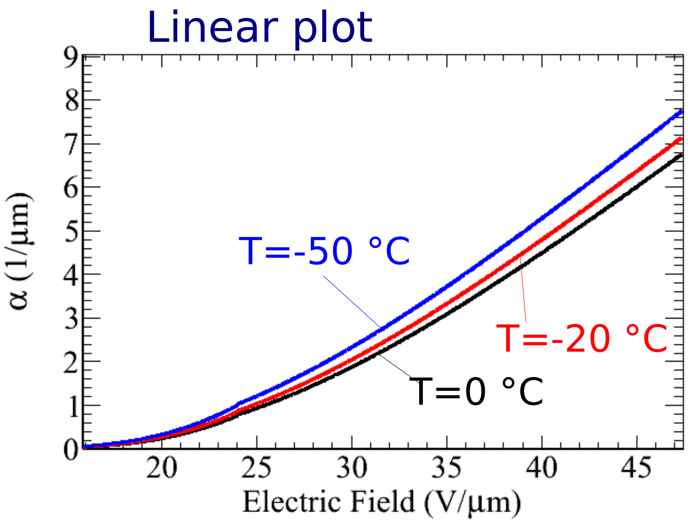
- **Charge multiplication above 150 V**
- **Lower temperatures: higher charge multiplication**

- **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

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



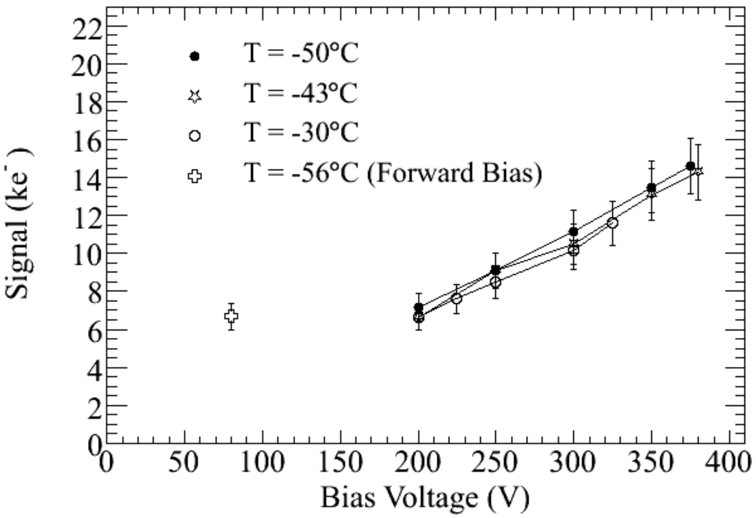


[Parameterisation: W. N. Grant, Solid-State Electronics, Vol. 16, 1973]

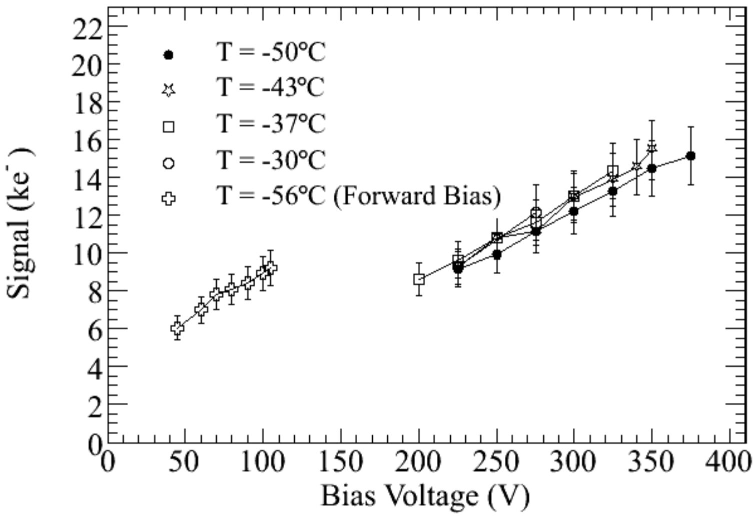
→ **If charge multiplication dominates: higher signal at lower temperature**

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

n-in-p



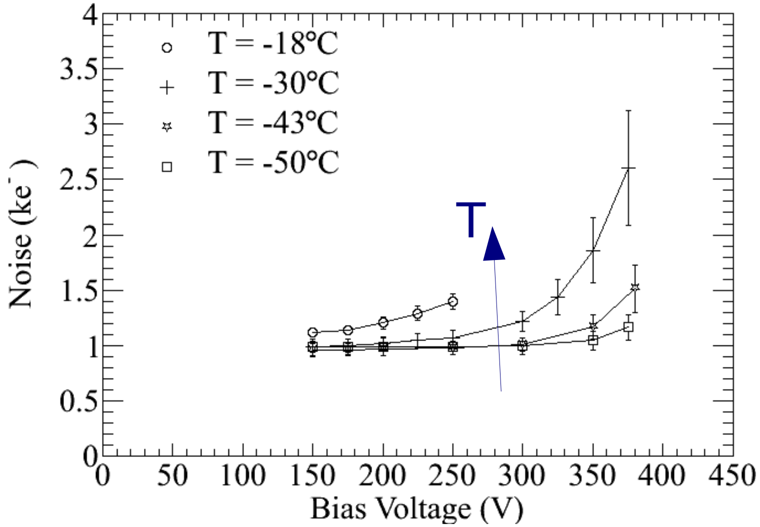
p-in-n



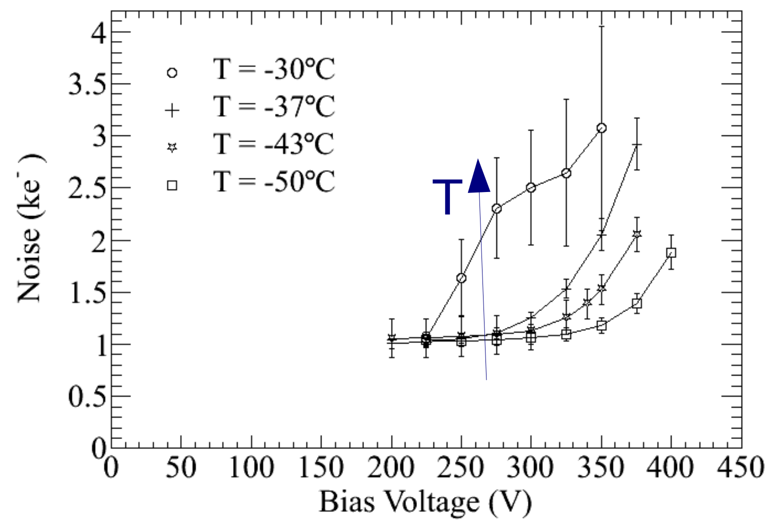
- **Forward bias: 7 ke⁻ at 80 V**
- **Reverse bias: 15 ke⁻ at 380 V**
- **Forward bias: 9 ke⁻ at 110 V**
- **Reverse bias: 15 ke⁻ at 350 V**
- **Maximum signal in n-in-p and p-in-n detector equal!**
- **No significant temperature dependence**

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

n-in-p



p-in-n



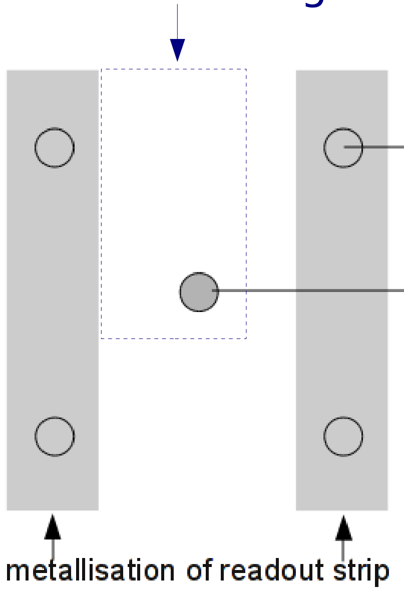
- **Strong noise increase with temperature – stronger than expected by standard shot noise parameterisation**
  - **Lower temperature improves signal-to-noise ratio strongly!**

UNI FREIBURG

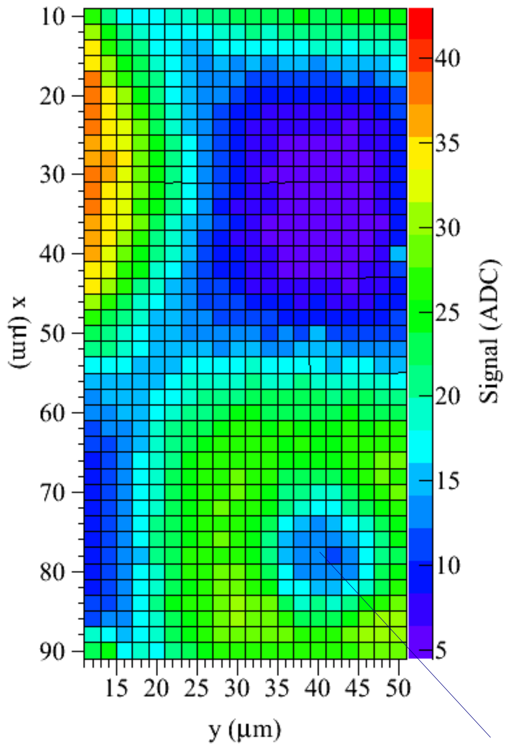
Laser Scan: $2x10^{16}$ n_{eq}/cm^2 , Low Voltage

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

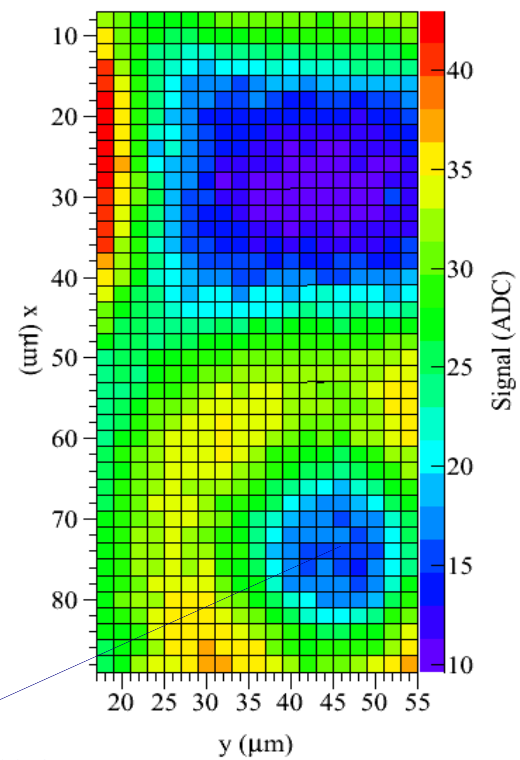
laser scan region



n-in-p, 100 V



p-in-n, 75 V



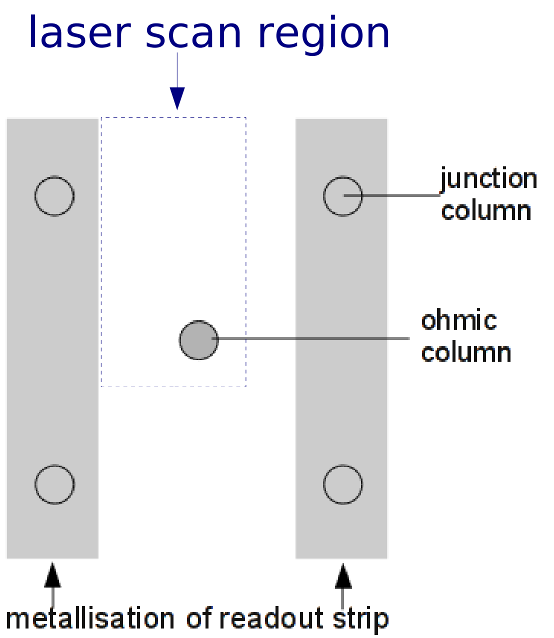
ohmic column

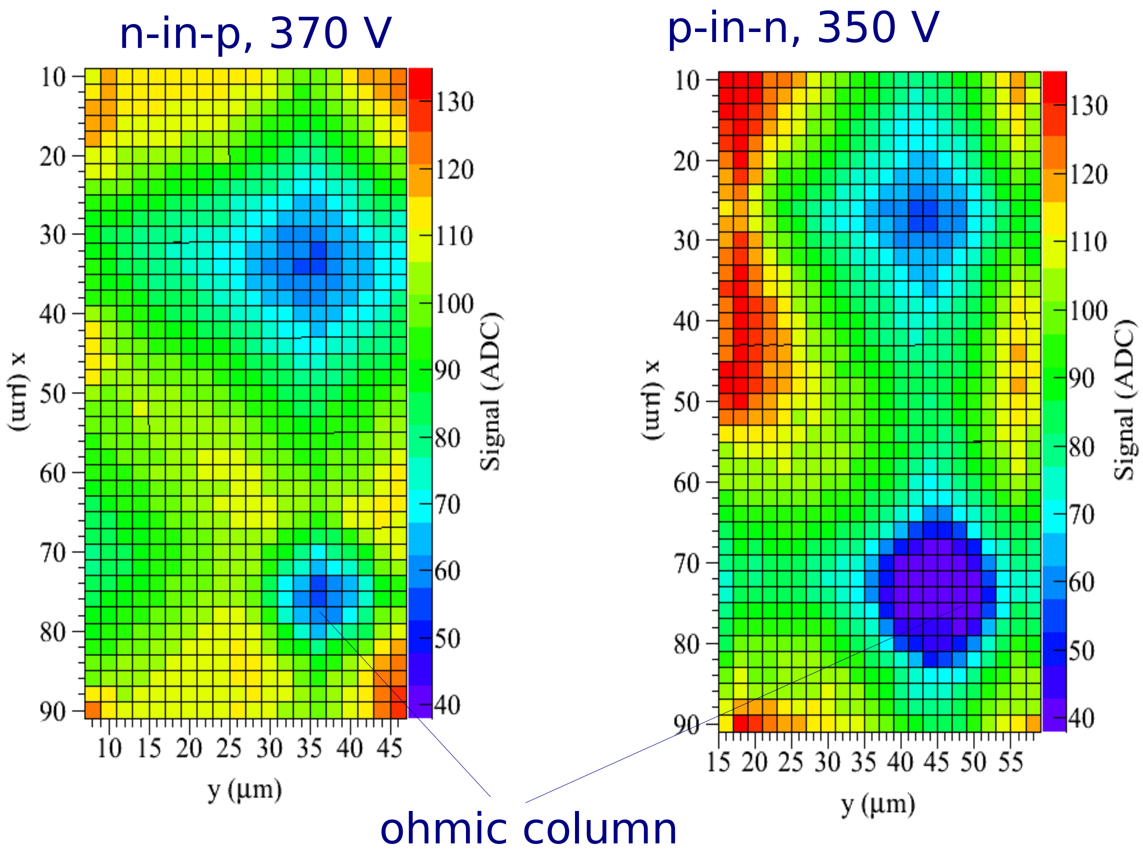
- **Not fully depleted**
- **Active region around junction column and ohmic column**

  → **Double junction**

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

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



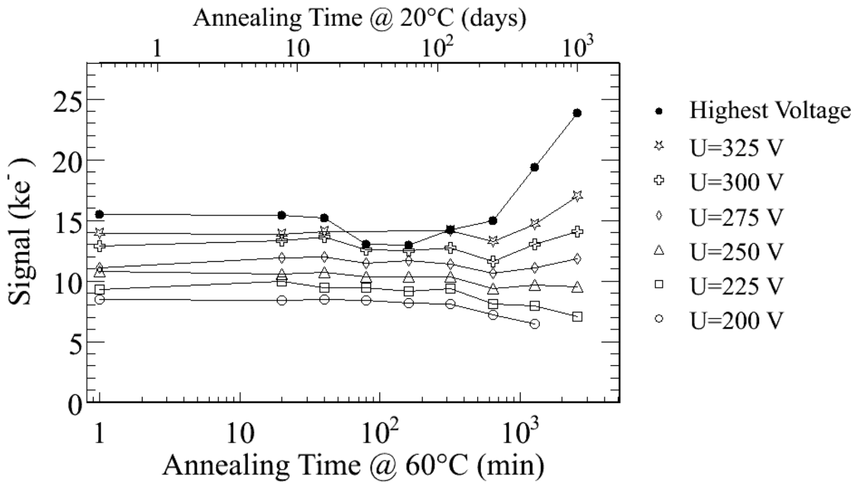


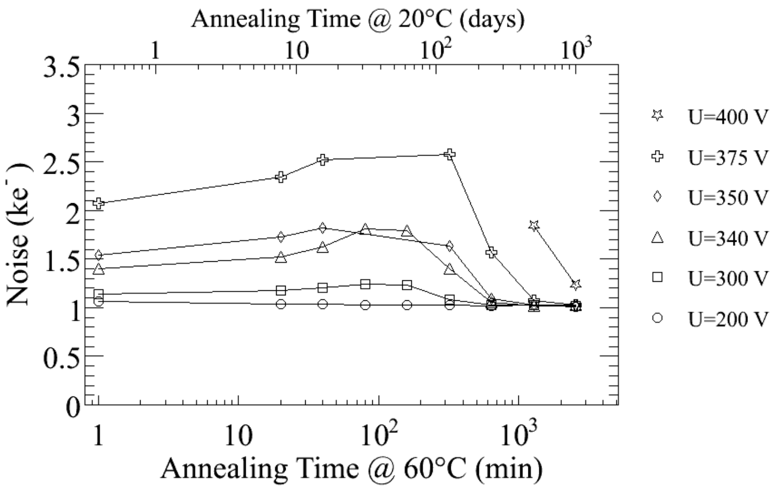
- **Low field region remains even at highest voltages**
- **N-type detectors: 50% larger column diameter visible**

UNI FREIBURG

Annealing: p-in-n, $2\times10^{16}\ n_{eq}/cm^2$

- **Signal, noise after annealing at 60°C (measurements at T=-43°C)**



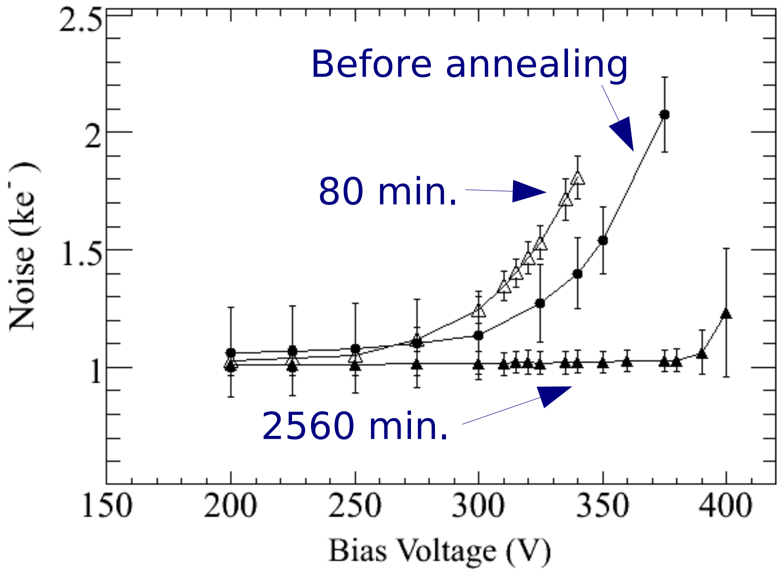


- **Signal increases after long annealing times**
- **Noise increases up to ~80 min (at 60°C), then decreases strongly**

  → Maximum of the noise is reached after completed "beneficial annealing"
- **Highest voltage, for which signal can be separated from noise, increases for long annealing times**

Annealing: p-in-n, 2x10[16] n_{eq}/cm[2] (Noise)

- **Noise: maximum reached after 80 min (at 60°C)**
- **"Short term annealing" increases noise**
- **"Long term annealing" decreases noise, increases signal**
  - **→ Extremely beneficial for signal-to-noise ratio!**
- **Leakage current decreases during complete annealing (as expected)**



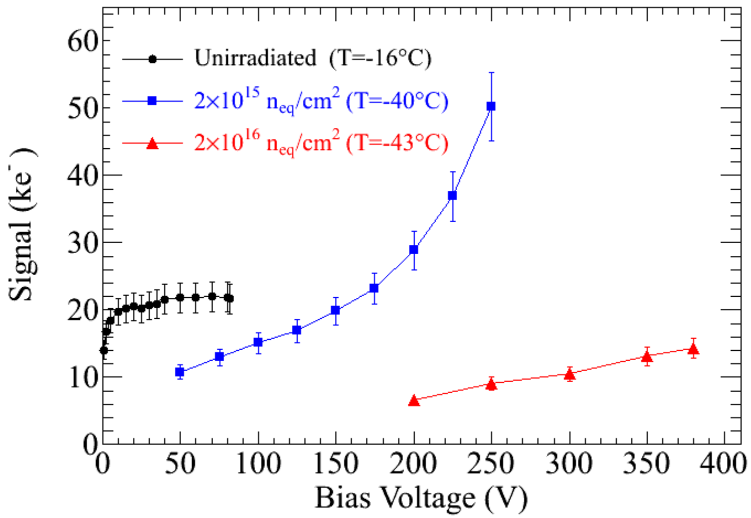
- **Why does the noise behave in the observed way? Can charge multiplication give an explanation?**
  - **Shot noise:** $ENC_{shot} = \sqrt{BIMF}\, e$ **[McIntyre, IEEE TED 13, 1966]**

  (B: shaper-dependent constant, I: leakage current, M: multiplication, F: excess noise factor, F~2 if only electrons multpliy and if M is sufficiently large)

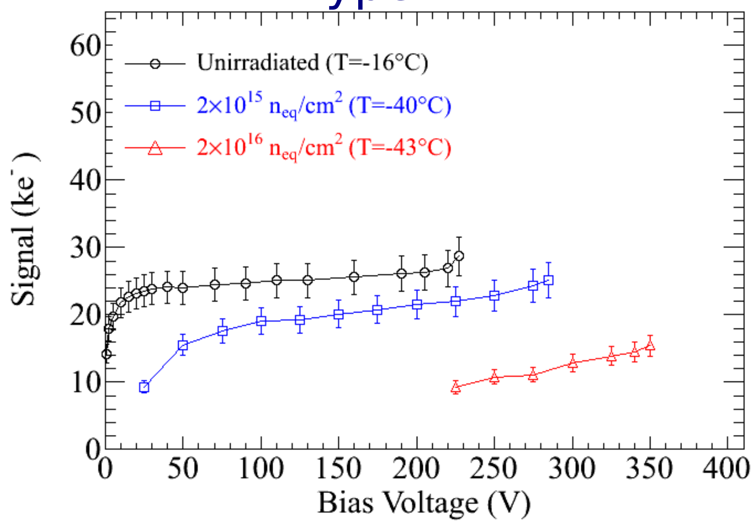
Summary

- **Charge multiplication in unirradiated n-type detector?**
- **Temperature dependence of signal and noise**
- **After fluence of $2x10^{16}$ 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!)
- **Annealing of p-in-n detectors studied**

p-type



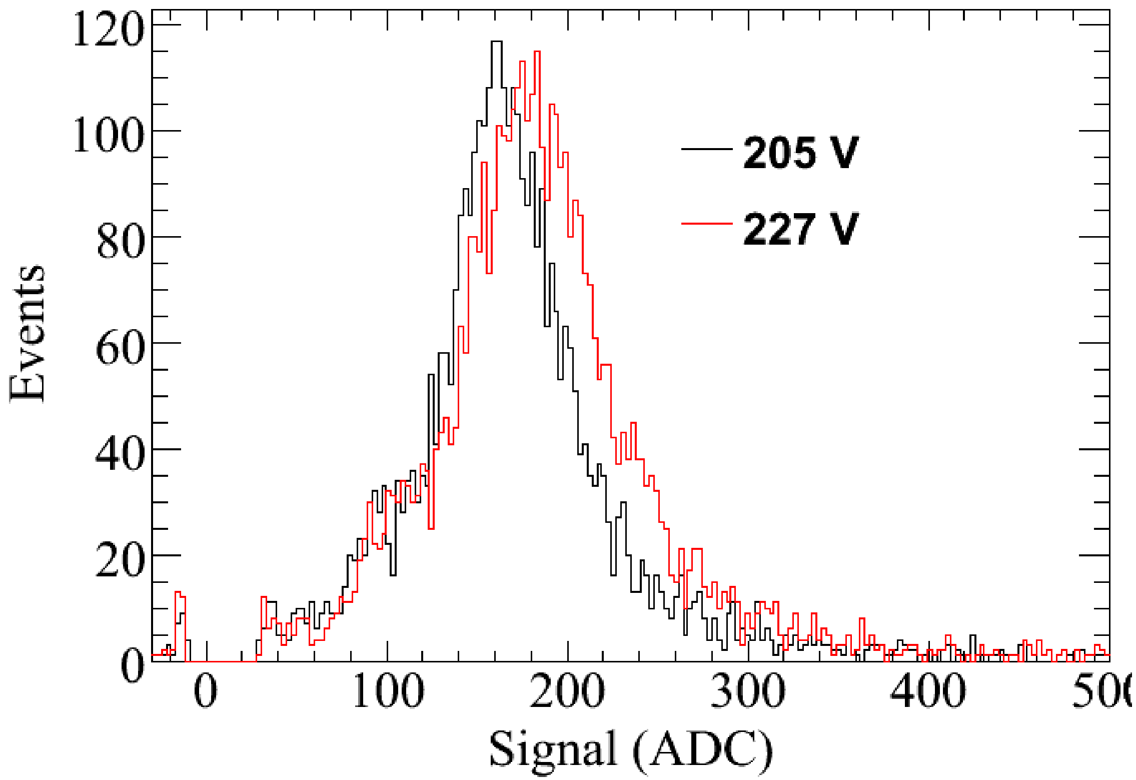
n-type



Backup Slides

Unirradiated, n-type: Signal Spectra

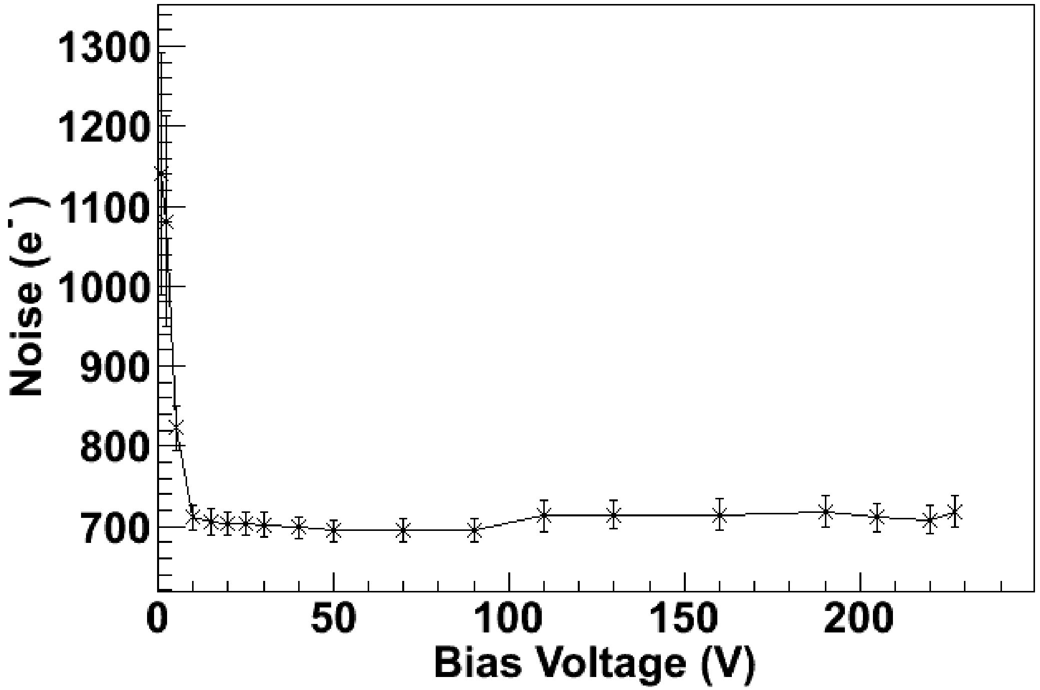
- Comparison of spectra at 205 V and 227 V (T=-17 °C)



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

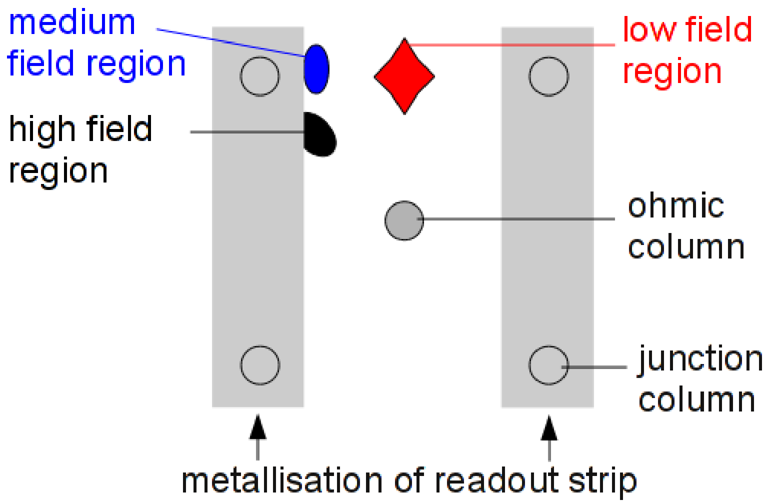
Unirradiated, n-type: Noise vs Voltage

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

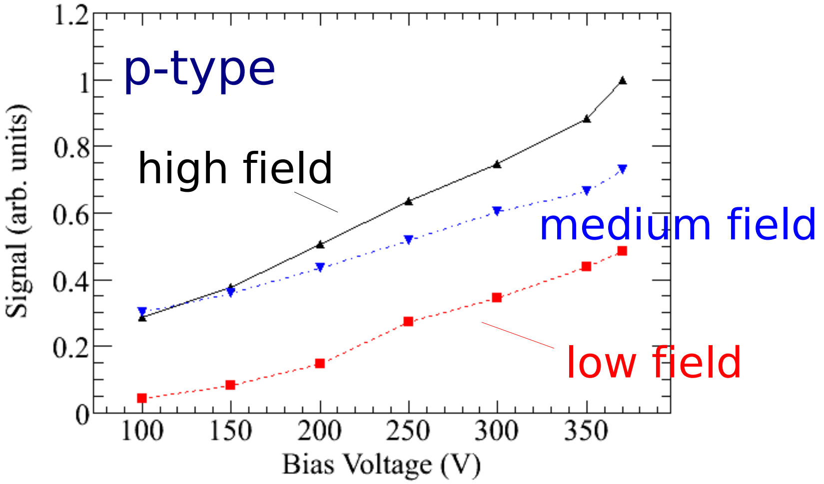


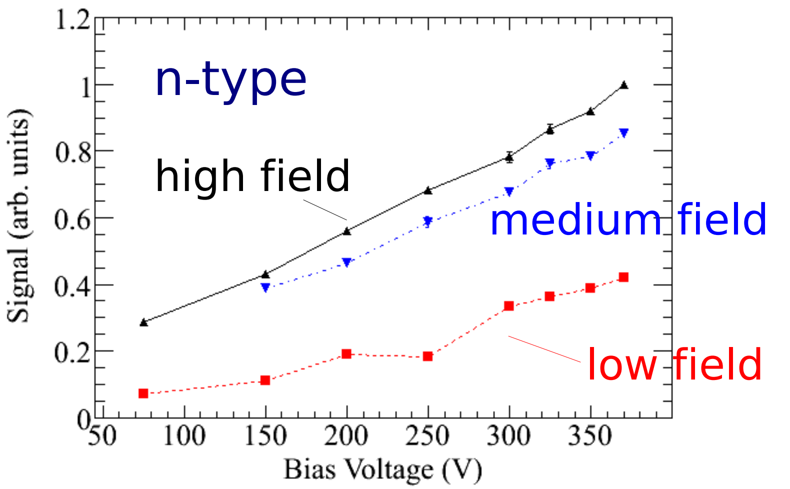
Laser: High Field vs. Low Field, $2x10^{16}$ n_{eq}/cm^2

- **Laser signals in different regions**



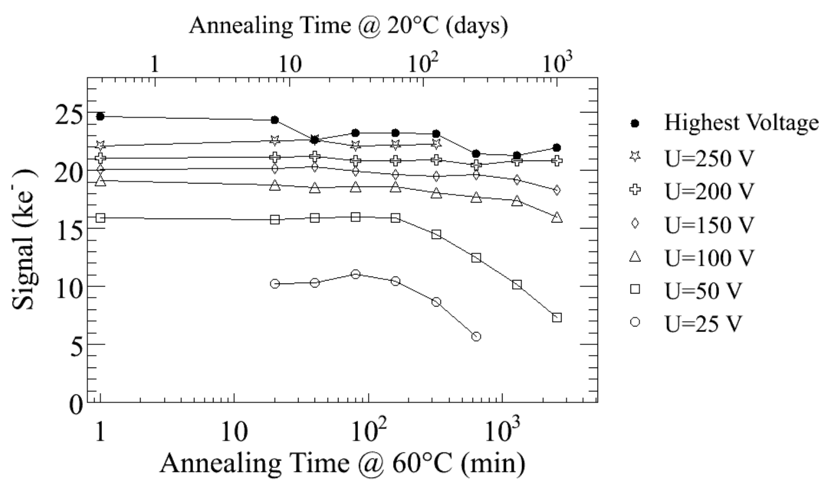
- **Signals normalised to highest signal**
  - **Only relative signals of laser measurements can be compared**
- **Results are similar for p-type and n-type**
  - **Low field region somewhat more expressed in n-type detector**

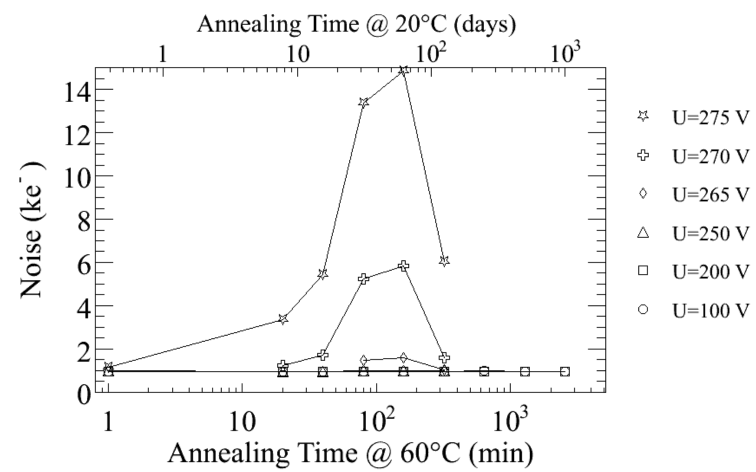




Annealing: p-in-n, $2x10^{15}$ n_{eq}/cm^2

- **Signal and noise after accelerated annealing at 60°C**





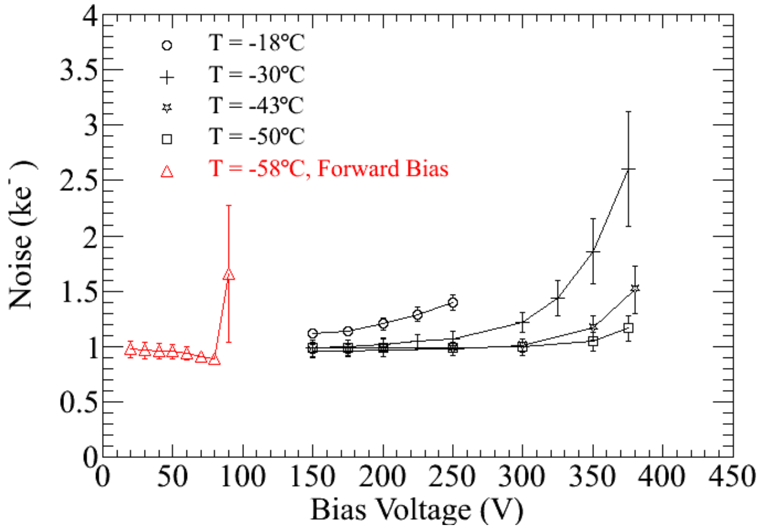
- **Noise increases up to ~160 min (at 60 °C), then decreases**
- **After 640 min (at 60°C): early breakdown occuring at ~230 V**

  → Bias voltages had to be limited, which explains the lower signal at the "Highest Voltage" after long annealing times

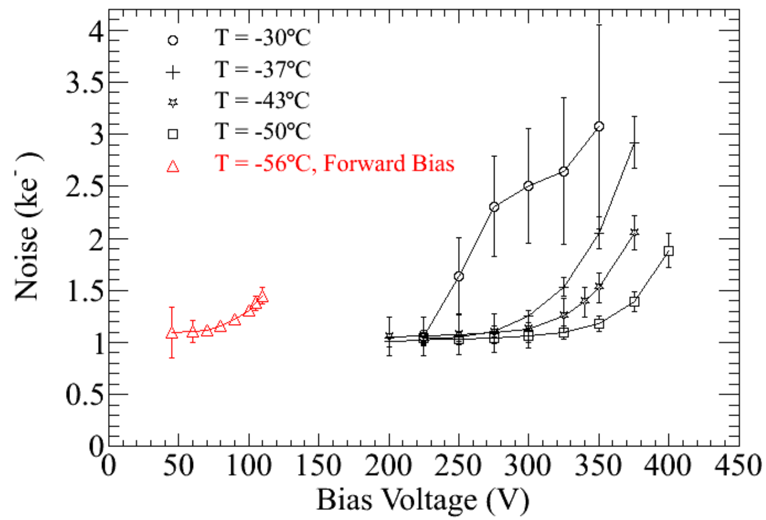
UNI FREIBURG

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

p-type



n-type

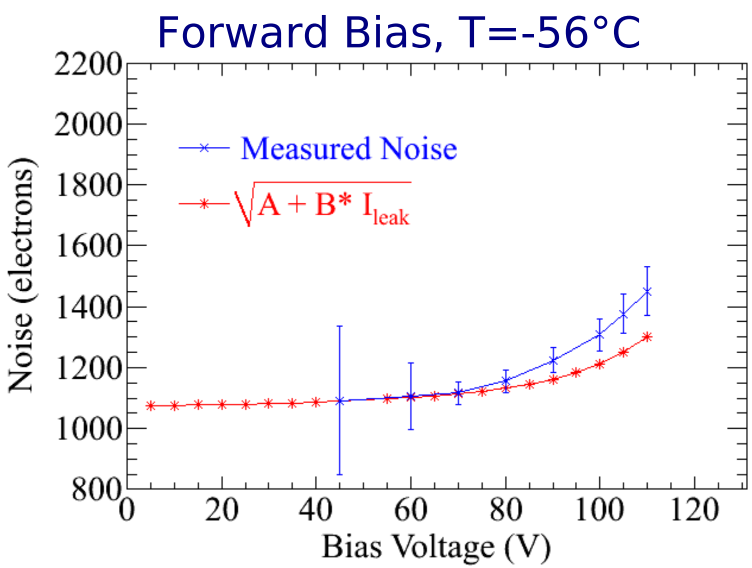


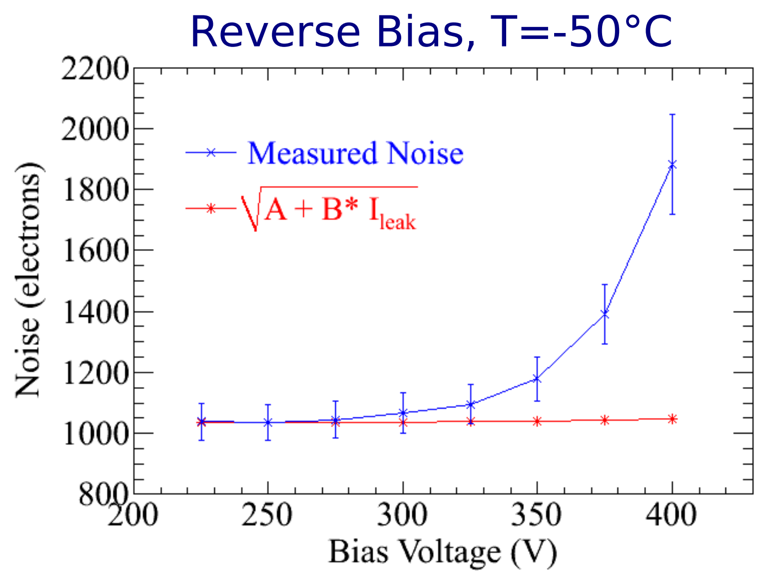
- **Strong noise increase with temperature – stronger than expected by standard shot noise parameterisation**
- **Forward bias:**
  - **Strange behaviour in p-type detector (noise decreasing with increasing bias)**
  - **Higher current, but lower noise than in reverse bias mode**

UNI FREIBURG

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

- **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)**