Semiconductor Photon Detectors
Part2

Gerhard Lutz

PNSensor GmbH, München

for the

MPI Semiconductor Laboratory, Otto Hahn Ring 6, D 81739 München

3rd Joint ILIAS-CERN-DESY Axion-WIMPs training-workshop

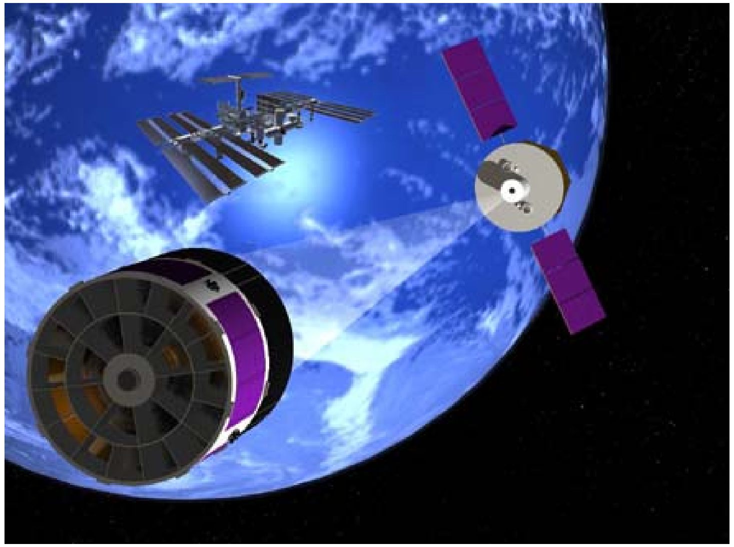
Patras, Greece
June 19-25, 2007

DEPFETs

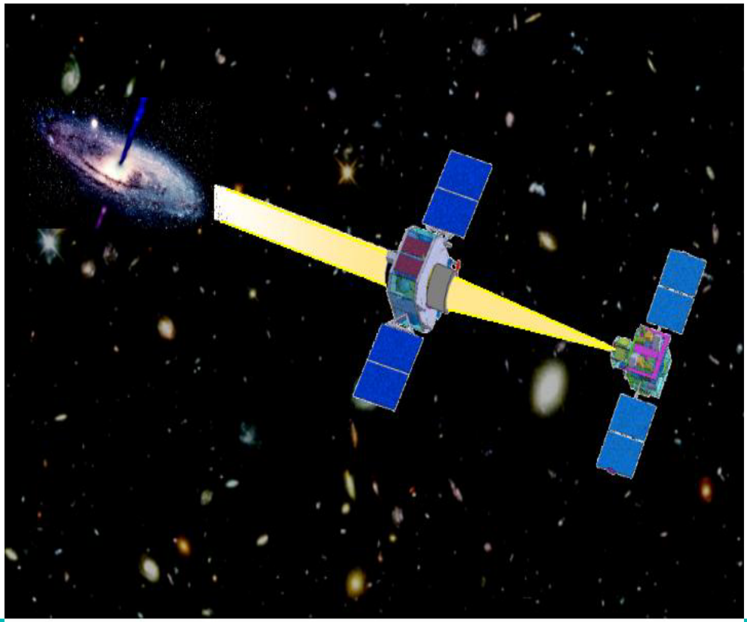
DEPFET Detectors in Institute Projects

X-ray Astronomy

- **XEUS** (X-ray Evolving Universe Spectroscopy)
  - **Scientific aim:**
  - **investigation of the universe at an early evolution stage:**
    - early black holes
    - evolution and clustering of galaxies
    - evolution of element synthesis
  - **Observation of distant faint objects:**
    - Large collection area
    - Large focal length (50m)
    - Separate satellites

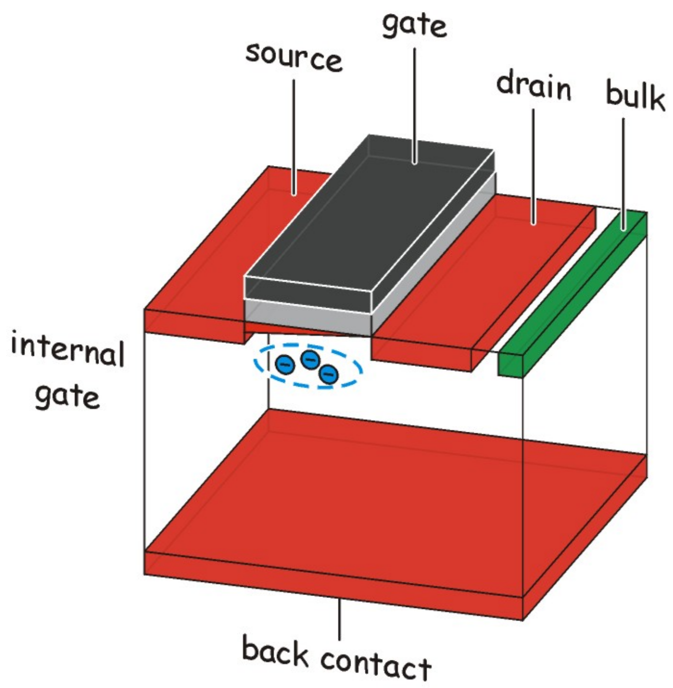


- **SIMBOL-X**
  - **First science objective :**
  - **astrophysics around black holes**
    - X-ray binaries Active Galactic Nuclei (supermassive active BHs)
    - The Galactic Centre (supermassive quiescent BHs)
  - **Hard X-ray sensitivity (0.5 to 80 keV)**
    - Large focal length (30m)
    - Separate satellites



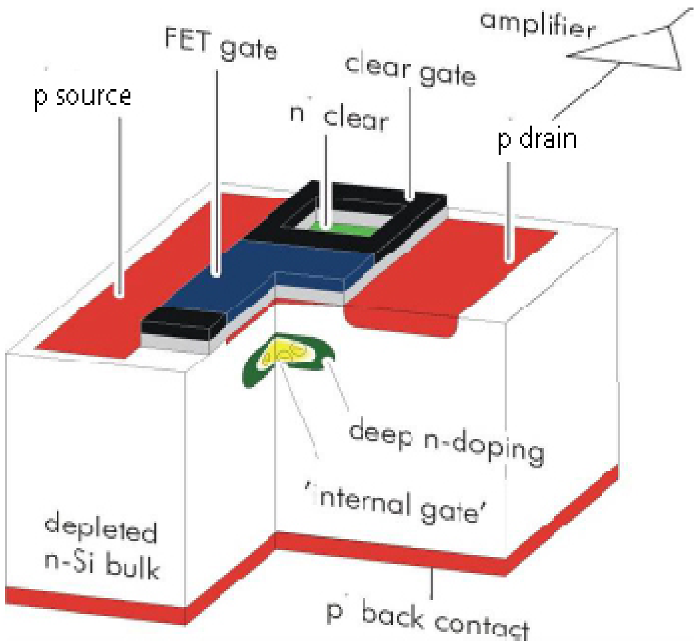
DEPFET Function principle

- Field effect transistor on top of fully depleted bulk
- All charge generated in fully depleted bulk
drifts into potential minimum underneath the transistor channel
steers the transistor current
- Clearing by positive pulse on clear electrode
- Combined function of sensor and amplifier

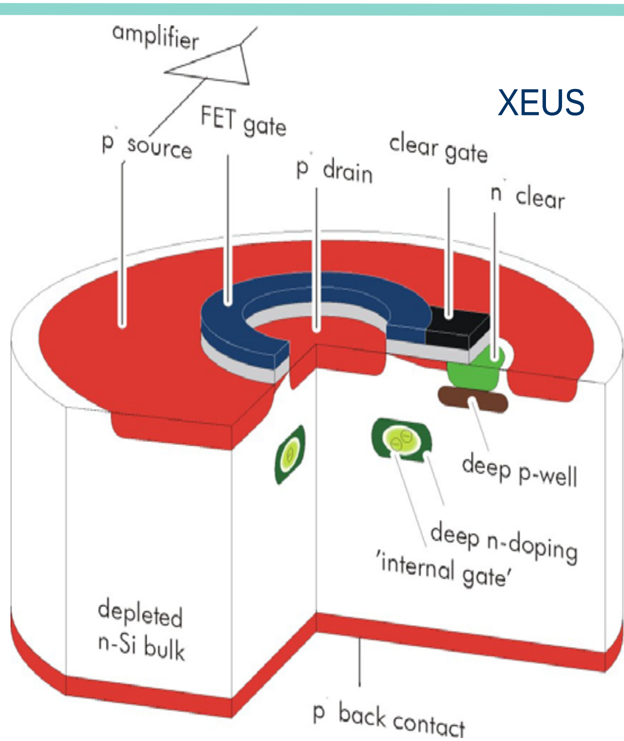


DEPFET properties

ILC



XEUS

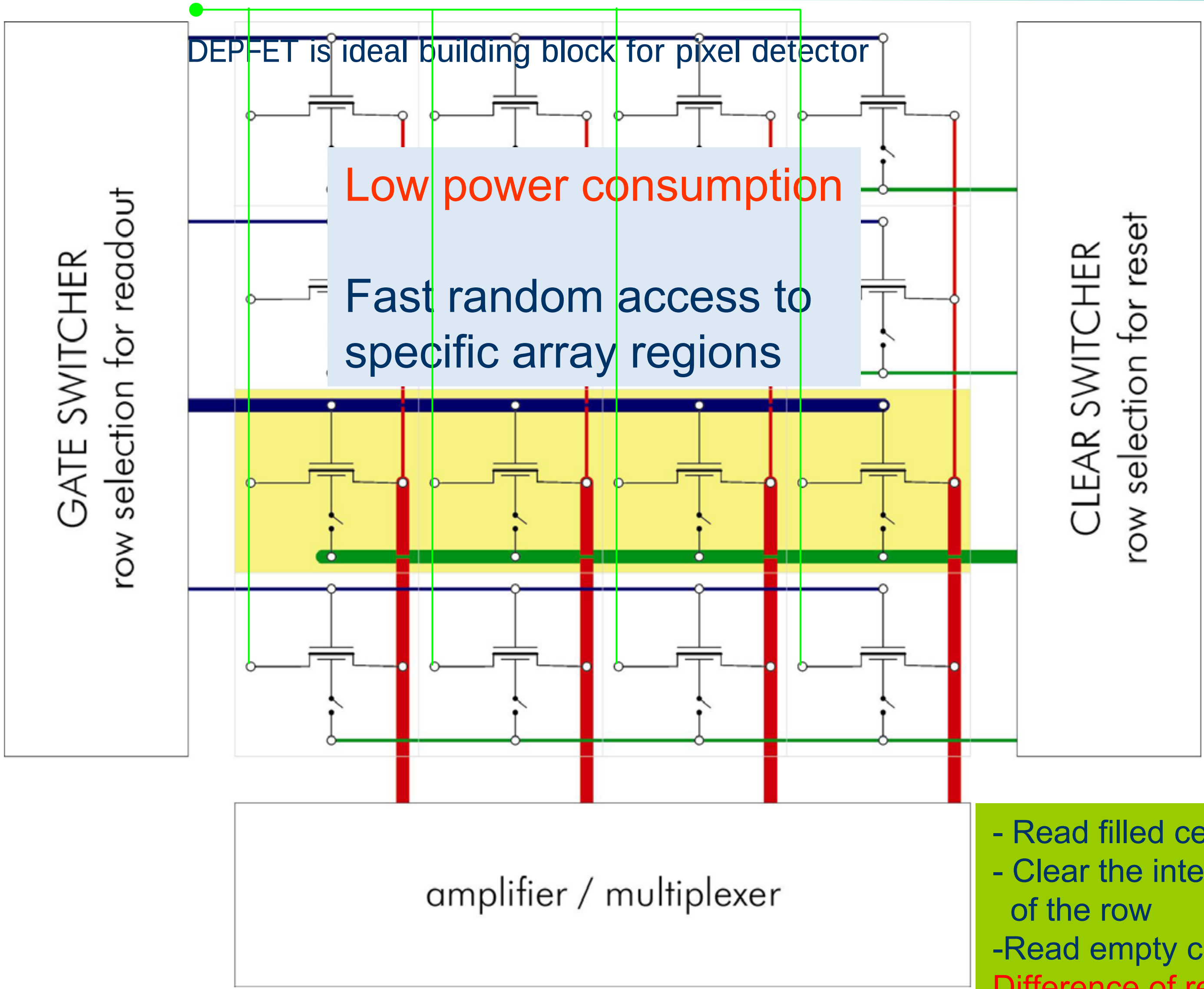


- Charge collection by drift mechanism over full wafer thickness
- low capacitance ▶ low noise
- Signal charge remains undisturbed by readout ▶ repeated readout
- Complete clearing of signal charge ▶ no reset noise
- Full sensitivity over whole bulk ▶ large signal for m.i.p.; X-ray sens.
- Thin radiation entrance window on backside ▶ X-ray sensitivity
- Charge collection also in turned off mode ▶ low power consumption
- Measurement at place of generation ▶ no charge transfer (loss) ▶

Operation over very large temperature range ▶ no cooling needed

DEPFET pixel matrix

DEPFET is ideal building block for pixel detector



Low power consumption

Fast random access to specific array regions

- Read filled cells of a row
- Clear the internal gates of the row
- Read empty cells

Difference of readings (filled/empty) mesures charge

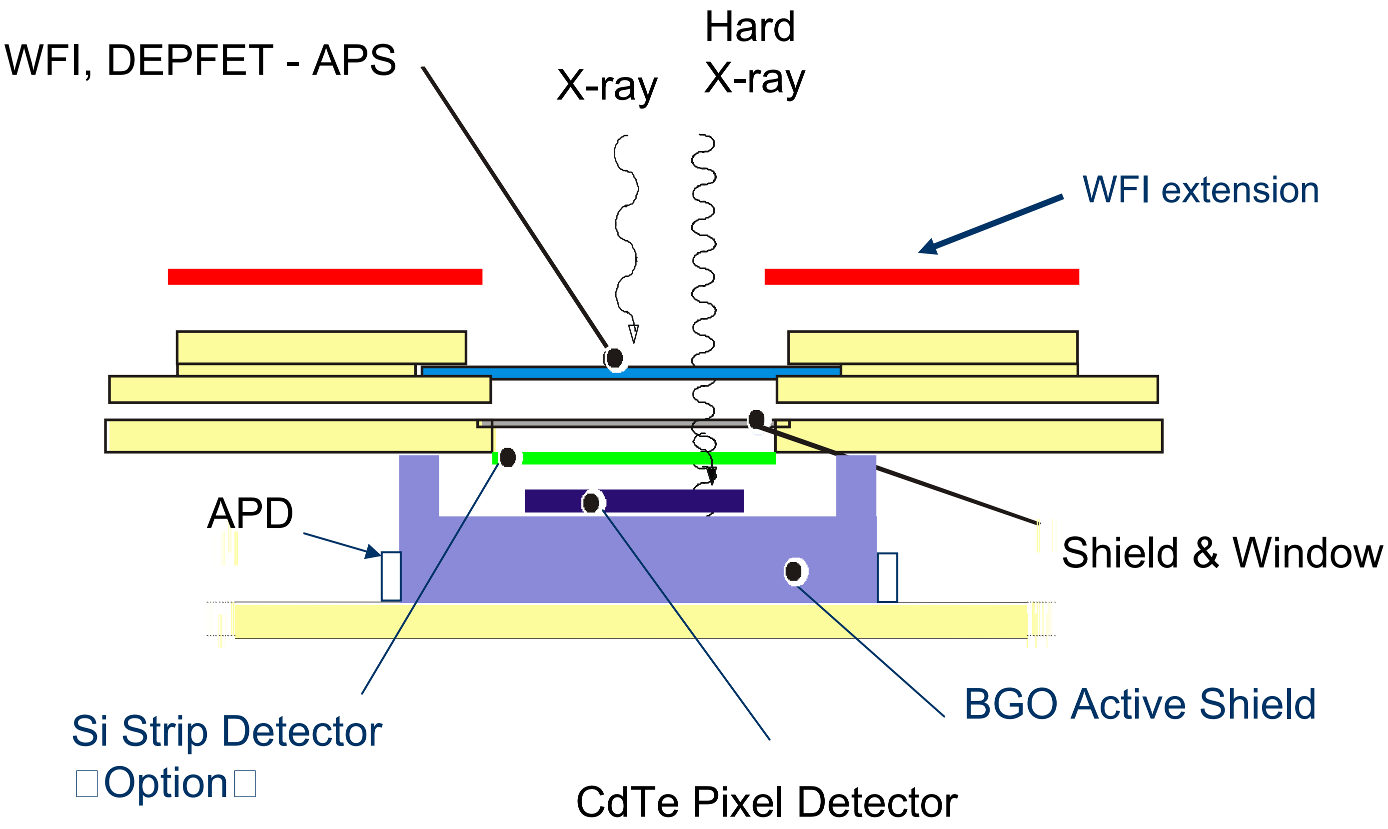
DEPFETs for XEUS

- Focal imaging: Wide Field Imager

  pixel size 75x75μm^2

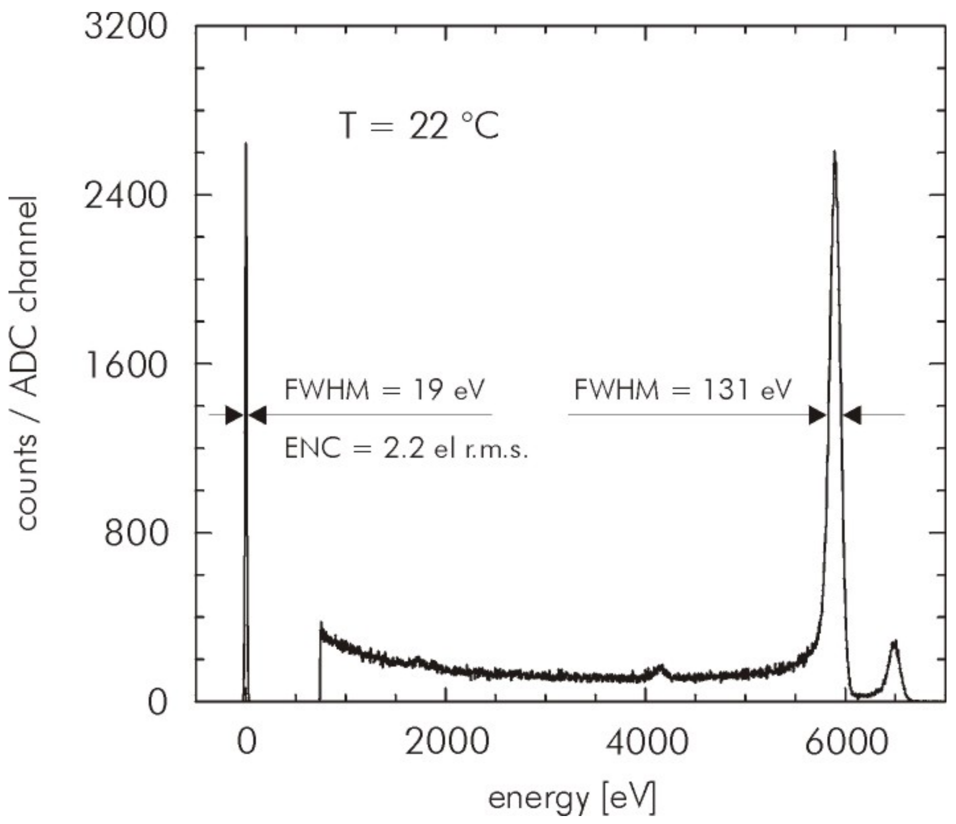
  1024x1024 pixels

  7.7x7.7 cm^2



XEUS DEPFET single pixel performance

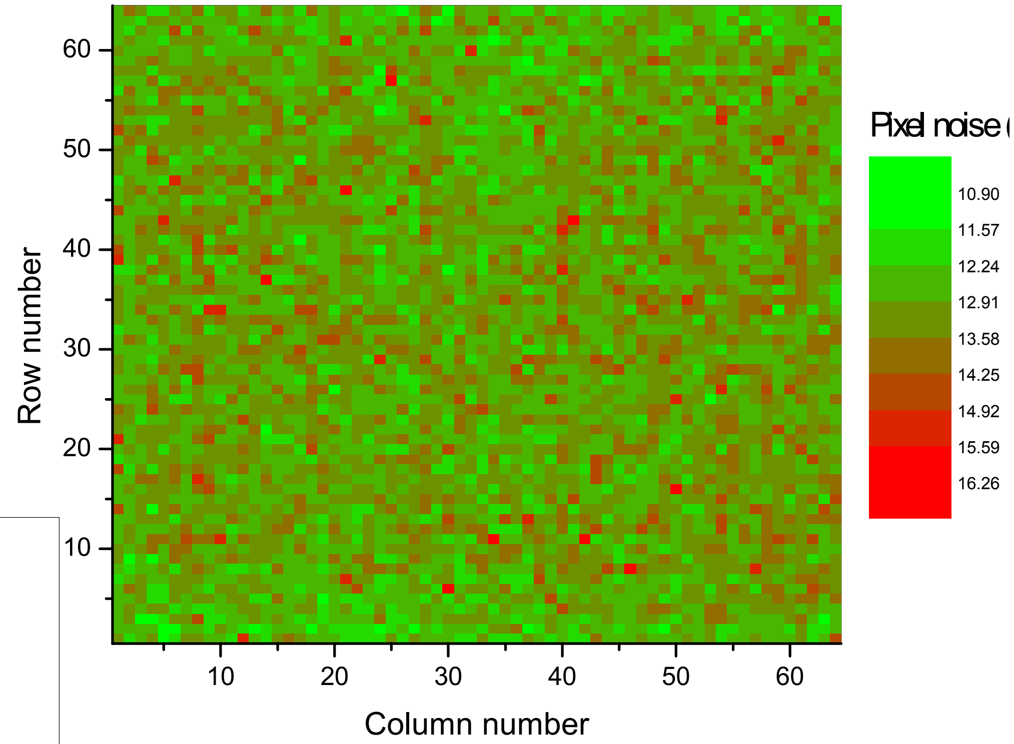
- Source follower readout
- **Pulsed clear** operation with **6µs time continuous** filter
- **Room temperature** (22° C)

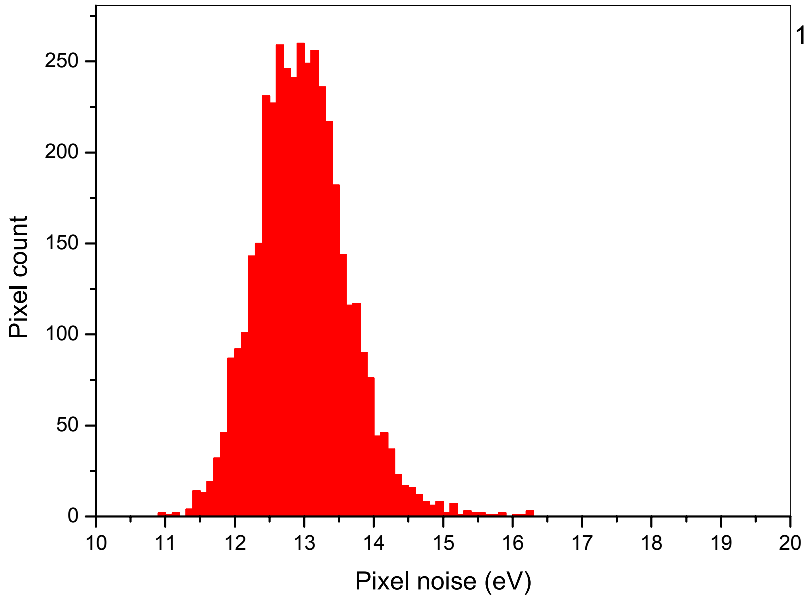


- **Noise peak:** σ = 2.2 e- ENC
- **Energy resolution at 5.9keV:** FWHM @ 5.9 keV = 131 eV

XEUS DEPFET matrix performance: noise

- Test of 64x64 pixel detector
- Noise performance at -40 C
- Average noise 3.8 electrons
- Noise dispersion ca. 10%

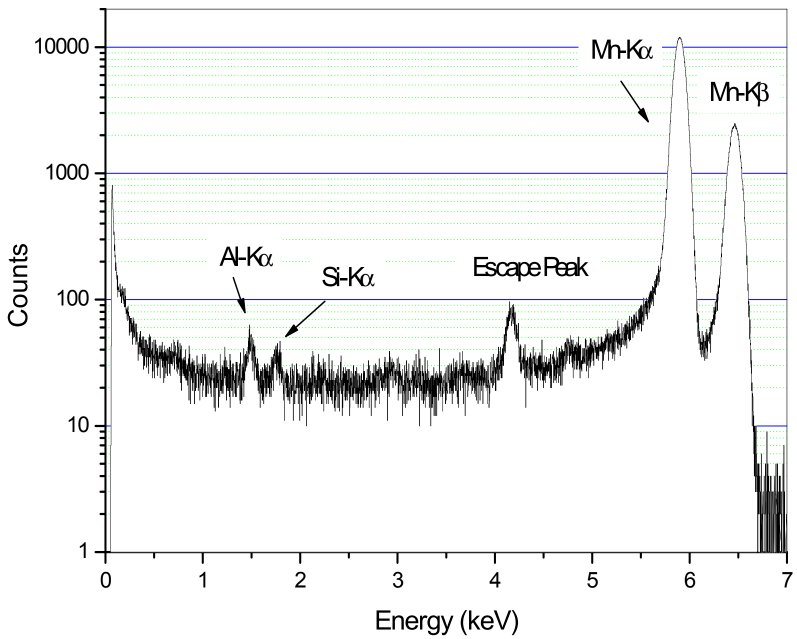




XEUS DEPFET matrix performance: spectrum

- Test of 64x64 pixel detector
- 55Fe spectrum at -50 C
- Pixel current 30 µA
- Line processing time 25 µs

- Energy resolution:
- 126 eV FWHM @ Mn-Ka Line
- corresponding to 4.9 e- ENC

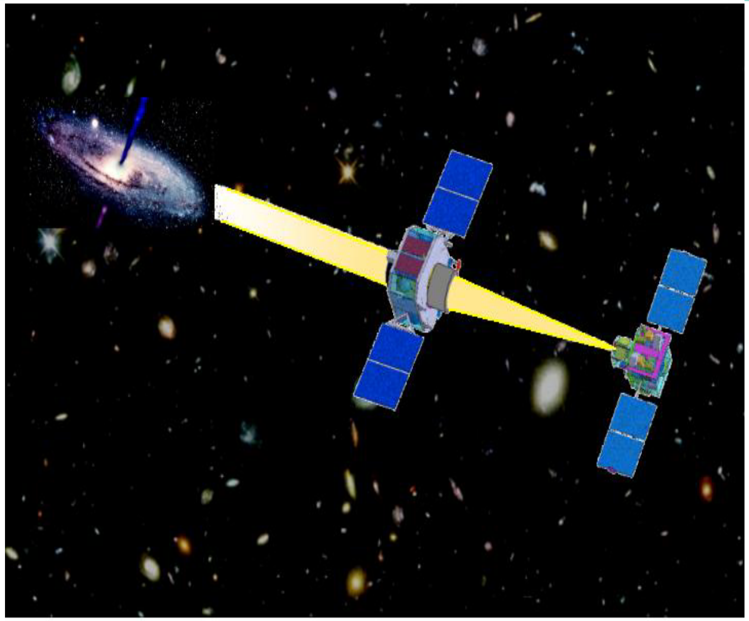


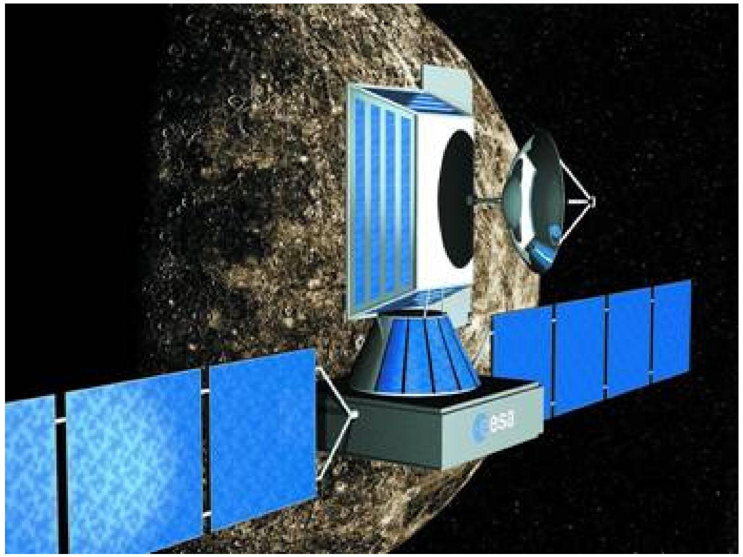
Macro Pixel Detectors

Macropixel DEPFET detectors

- Pixel detectors with large cell size needed in order to match pixel size to optical property of telescope

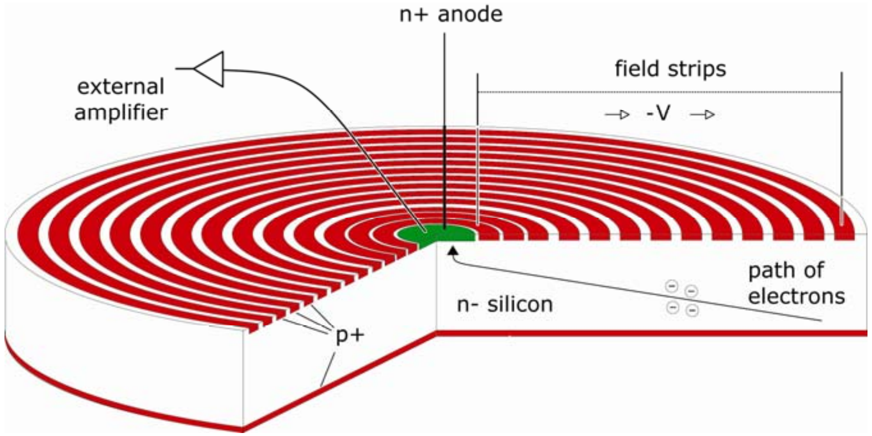
- Examples:
  - SIMBOL X
    - **astrophysics around black holes**
      X-ray binaries, Active Galactic Nuclei
      The Galactic Centre
    - **Hard X-ray sensitivity (0.5 to 80 keV)**
      Large focal length (30m)
      Separate satellites
  - BEPI Colombo
    Mercury planetary orbiter
    - X-ray spectrometer

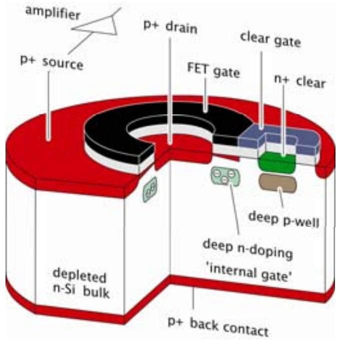




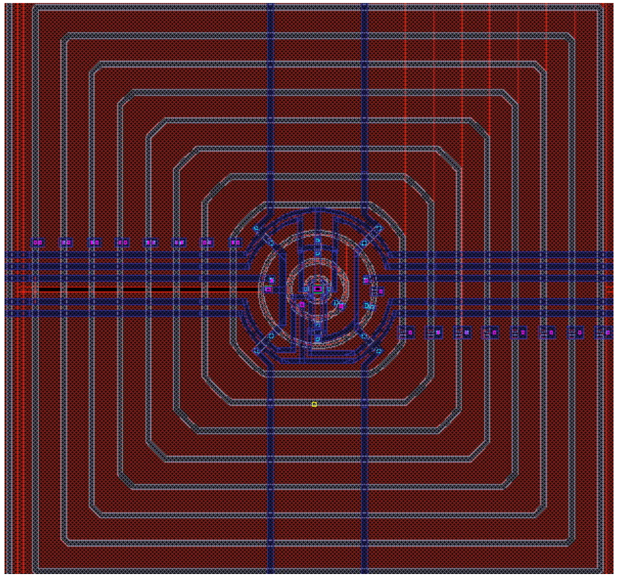
Macropixel DEPFET detectors

- Combination of SDD (Silicon Drift Diode) with DEPFET



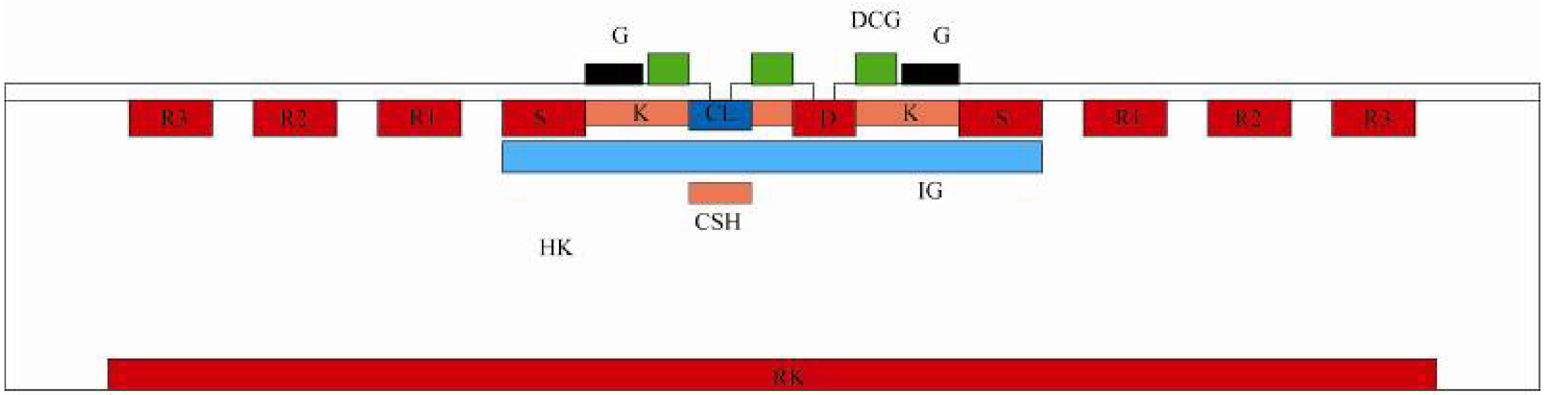


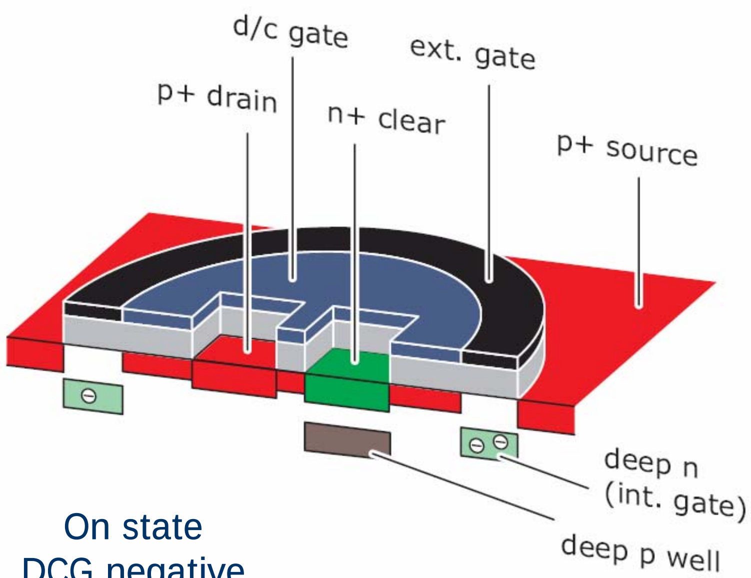
- Each cell consist of drift diode with DEPFET as readout element
- Cell size can be chosen (adapted to the application) over a very wide range



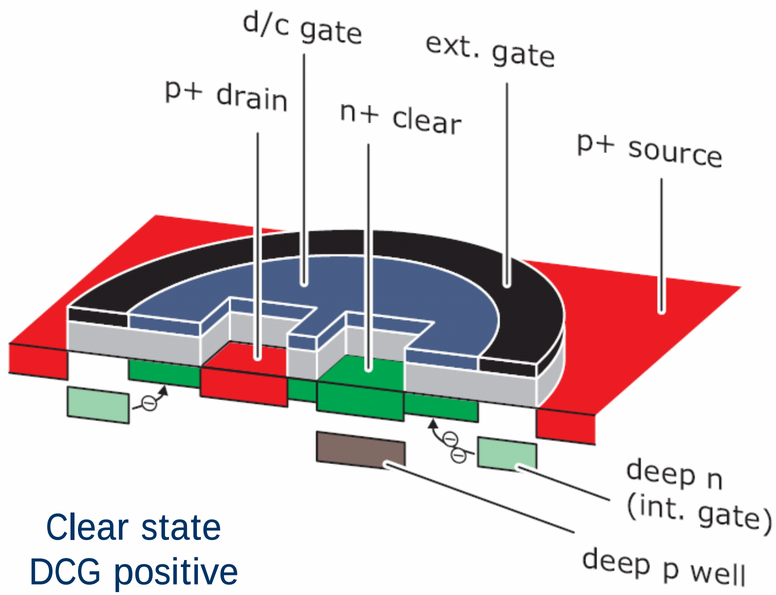
DCG type DEPFET

- New type of DEPFET allows operation with lower clear voltages





On state
DCG negative

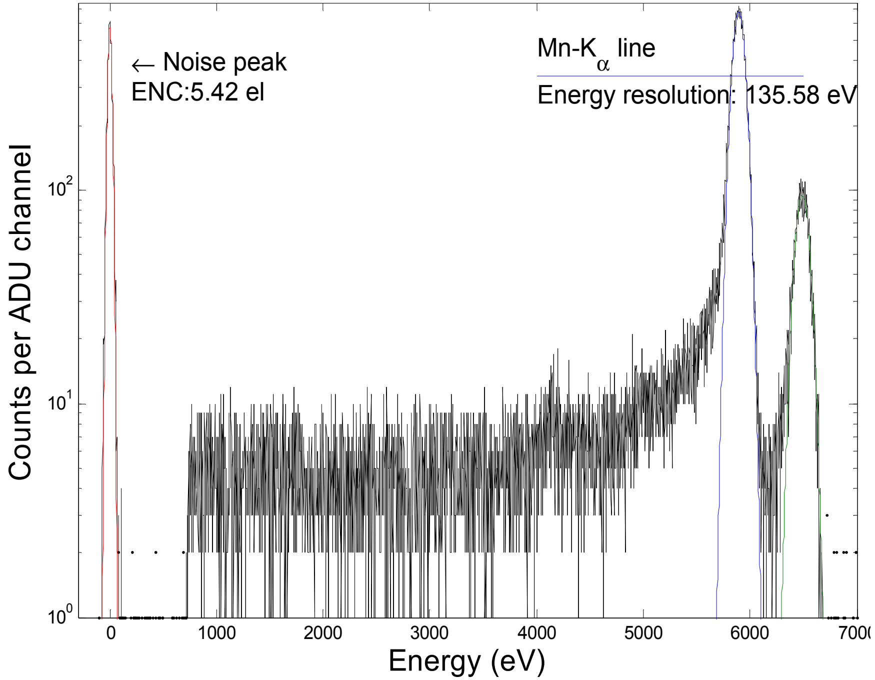


Clear state
DCG positive

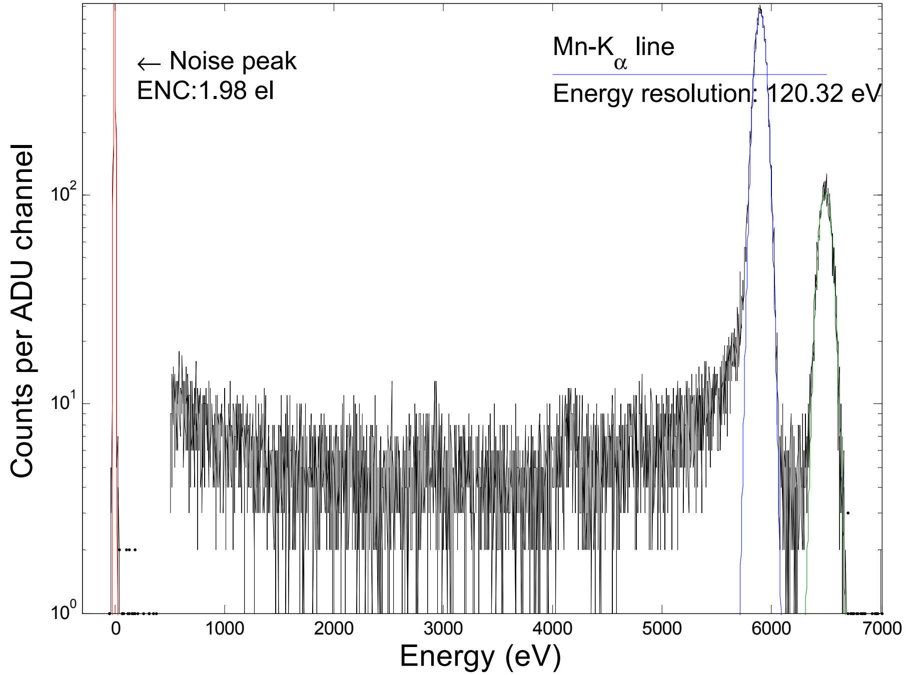
Macropixel DEPFET detectors: results

- Devices produced: Single pixels and 4x4 matrices of 1x1mm2 pixel size with normal and DCG DEPFETS
- In production: 64x64 matrices with 0.5x0.5 mm2 pixel size

Single cell measurements at different conditions for the two device types



DCG type: T= -20 C, shaping 6µs, I=100µA
Noise ENC=5.4 electrons



„normal“ type: T= -30 C, shaping 6µs, I=40µA
Noise ENC=2 electrons

Difference in performance is due to the large chosen geometry in the DCG type

Single (optical) photon detection

Single (optical) photon detection

- Photon Detectors described so far can be used for:
  - Single X-ray photon detection producing many electrons/photon
  - Measure energy, position and time of arrival
  - For optical photons only flux measurements are possible
- New applications in
  - High Time Resolution Astronomy (HTRA) and
  - Astroparticle Physics

require

- detection of single optical photons with
  - high quantum efficiency

Detector requirements

- **High time resolution astronomy:**
  - Observation of faint (distant) periodically varying objects producing sometimes less than one (optical) photon per period:
    - Rotating neutron stars
    - Close binary objects (e.g. rotating around black holes)
  - Time resolution (frame rate) better than 1 millisecond
    - less than 1 electron on average per frame
    - Sensitivity for single electron
- **Astro-Particle Physics:**
  - Observation of high energy showers in atmosphere:
    - Optical photons from scintillation and Cerenkov light
    - Night sky background
  - High time resolution (ns) for
    - Suppression of Night sky background
    - Measurement of shower angle

Single Optical Photon Detection

- **Conversion properties**:
  - Only one electron produced in conversion process (photoelectric effect)
  - Short penetration length for blue light in silicon

- **Single optical photon detection** requires either
  - Improvement of charge measuring precision to a small fraction of the elementary charge
    possible with DEPFET ping-pong RNDR structures but requires very large readout time

  or

  - An intrinsic charge multiplication process (avalanche multiplication)
    used since considerable time but has problems with quantum efficiency due to obstruction of the entrance window

Both methods are being developed at MPI

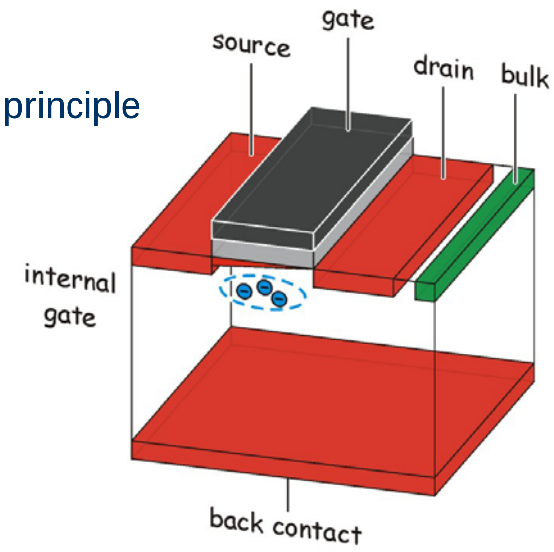
RNDR (Ping-Pong) Readout

RNDR (Repeated Non Destructive Read) DEPFETs

- Measure charge by difference of DEPFET current with/without charge in internal gate
- Do not destroy charge when removing from internal gate but
- Move charge to intermediate storage place so as to be able to move it back to internal gate for renewed measurement
- Charge may also be moved repeatedly between internal gates of two neighboring DEPFETs
- Serial noise drops with sqare root of number of measurements
- This holds also for serial 1/f noise

- Closed (circular) and Open (linear) double DEPFET structures produced
- Results of linear structures to be presented

DEPFET principle



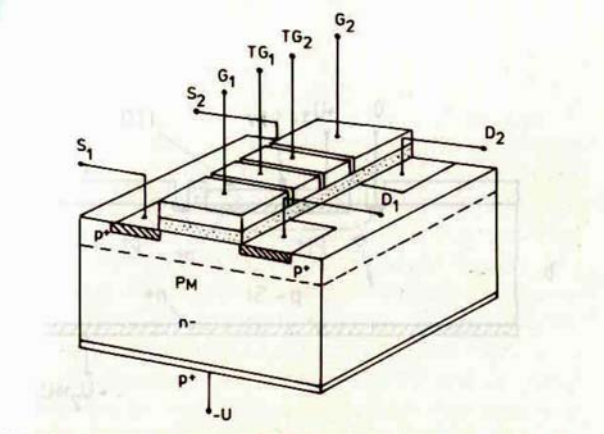
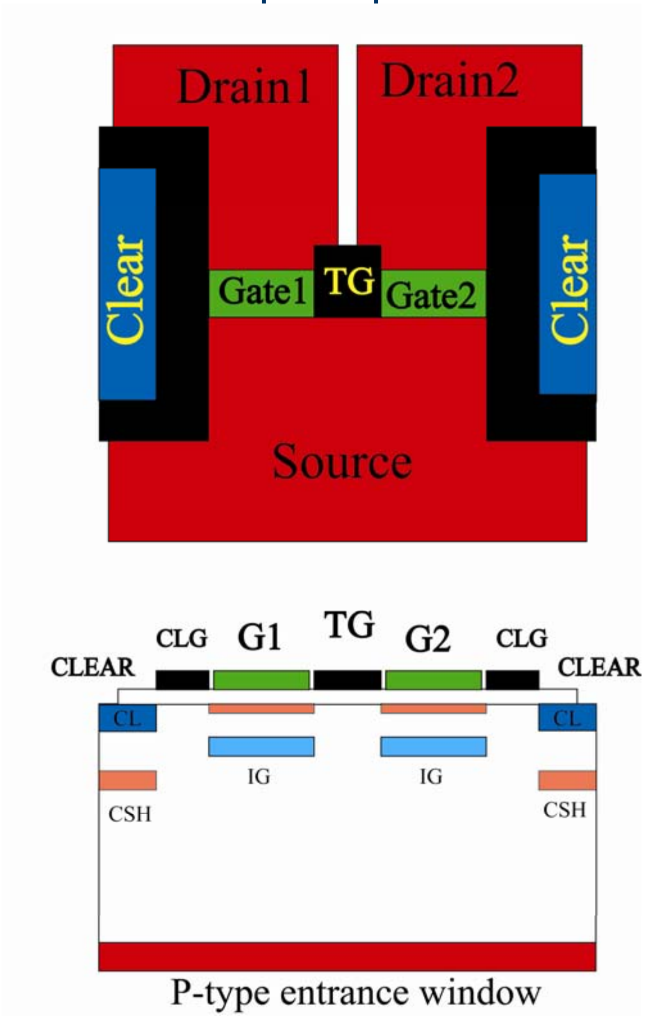


Fig. 29. Double gate DEPMOS transistor with transfer gates TG_1 and TG_2. Charge can be shifted from gate G_1 to gate G_2 for differential measurements.

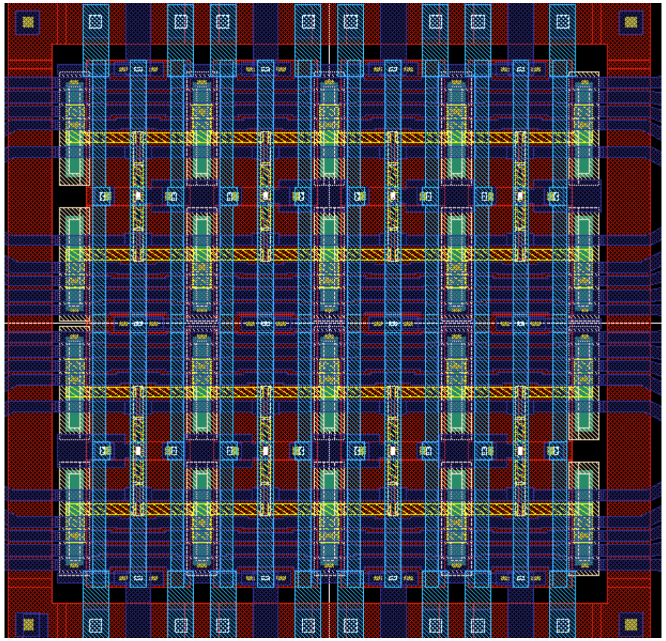
J.Kemmer and G.Lutz: New Detector Concepts, NIM A253 (1987) 365-377

RNDR linear structure

- Function principle



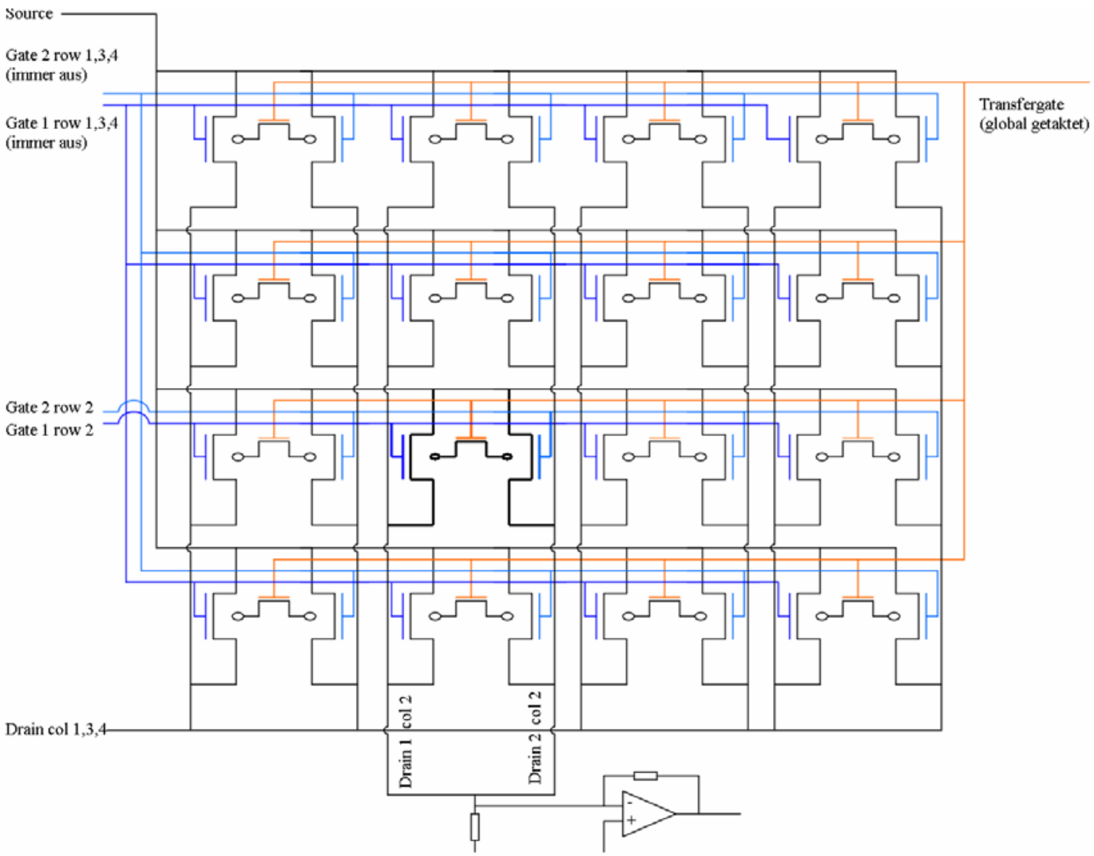
Layout of 4x4 matrix : 75 µm pixels



RNDR tests: measuring setup

Authors: S.Wölfl, G. Lutz, L. Strüder, P. Lechner, R.H. Richter, J. Treis, S. Herrmann, M. Porro

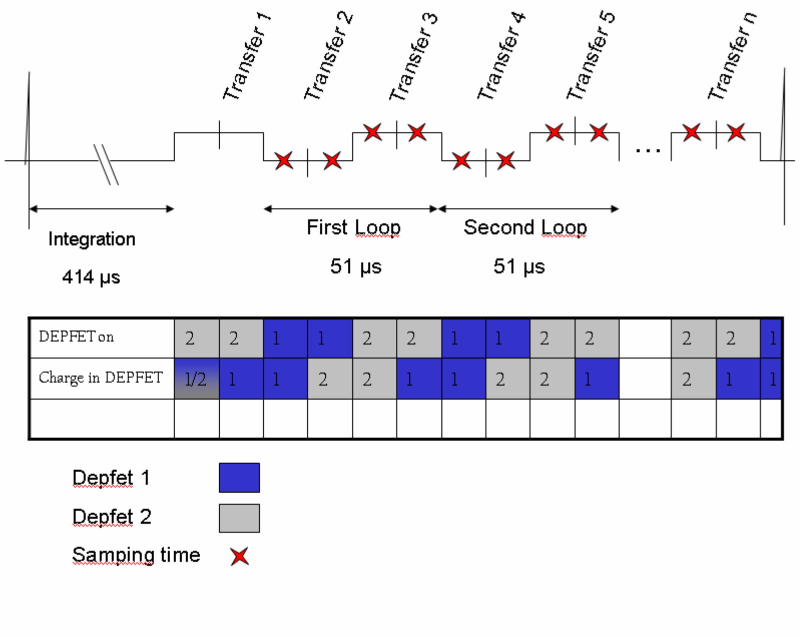
- Test of one pixel in a 4x4 matrix
- Turn on one DEPFET at a time (with the help of the corresponding gate)
- Measure current with full and empty gate (before and after transfer of charge to neighbor)
- Calculate current difference (as measure of the signal charge)
- Repeat procedure for neighbour DEPFET
- Repeat complete cycle many times
- Average the current differences of all measurements



RNDR tests: operating conditions

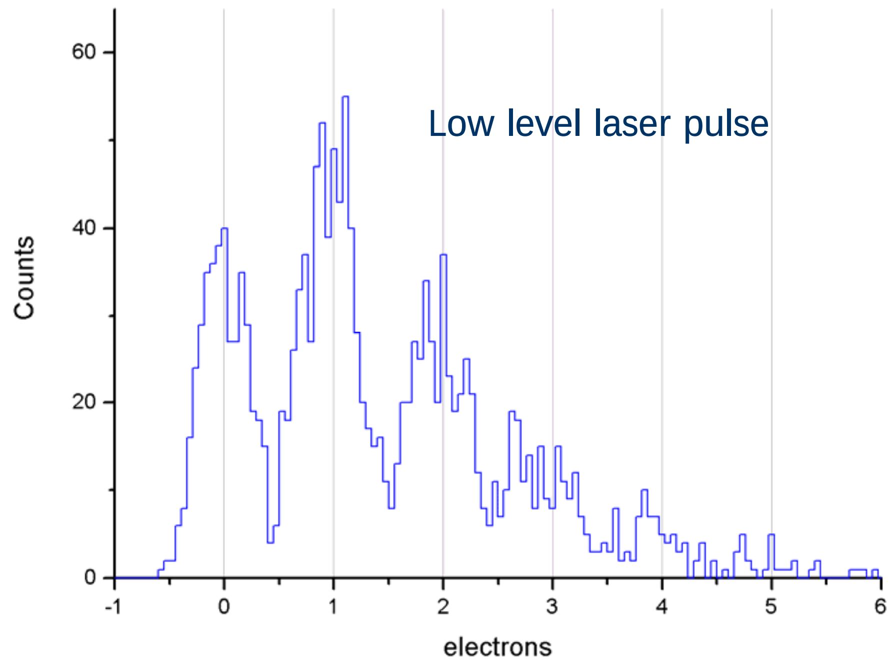
Authors: *S.Wölfl, G. Lutz, L. Strüder, P. Lechner, R.H. Richter, J. Treis, S. Herrmann, M. Porro*

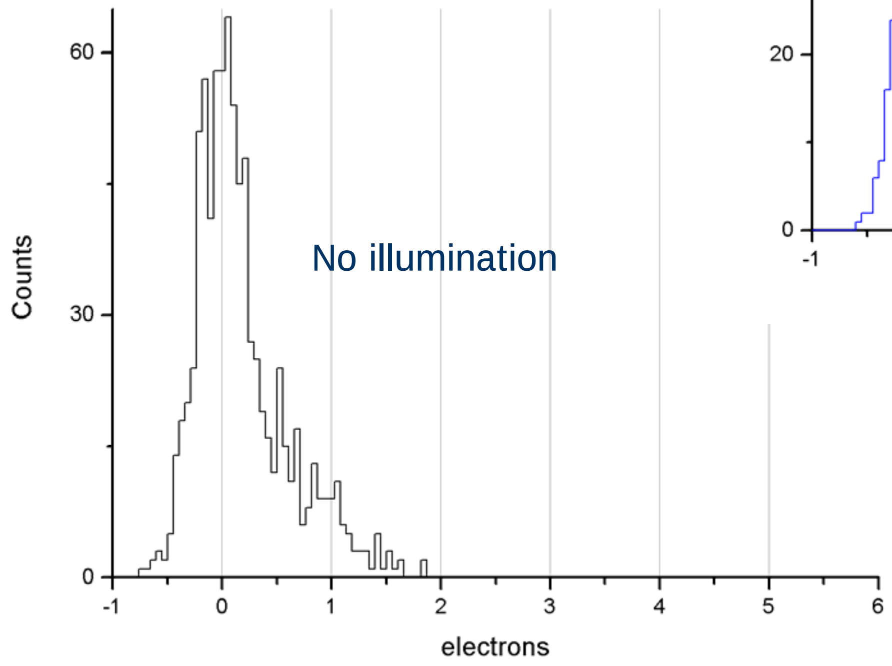
- Operating Temperature -45 C
- Leakage current: 1 electron in 14 ms
- Single sampling averages current over 10 µs
- 1 loop = 4 single samplings takes 51 µs
- Injection of laser pulse during integration time of 414 µs



RNDR tests: noise and very low level laser light

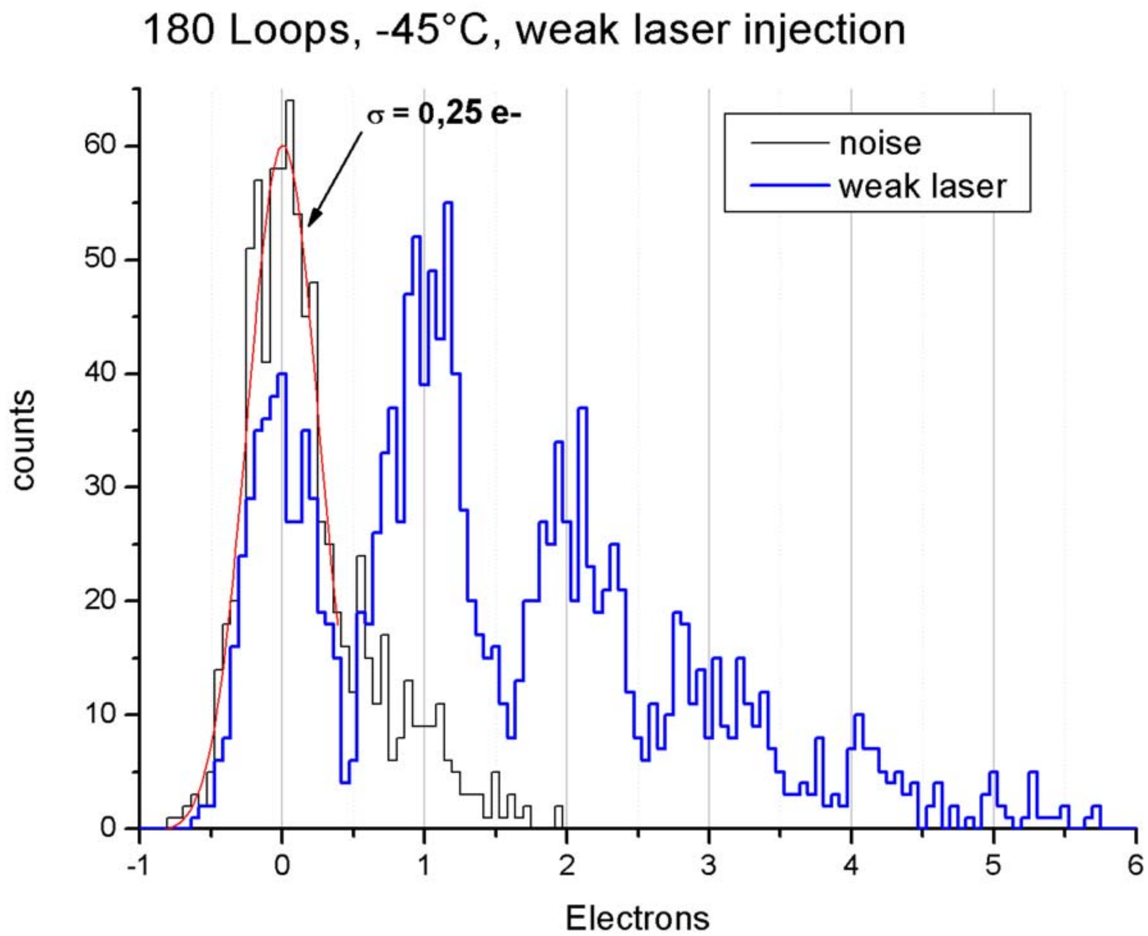
- Measurement of charge with 180 loops corresponding to 9.2 ms total measuring time
- Charge calibration with ^{55}Fe source





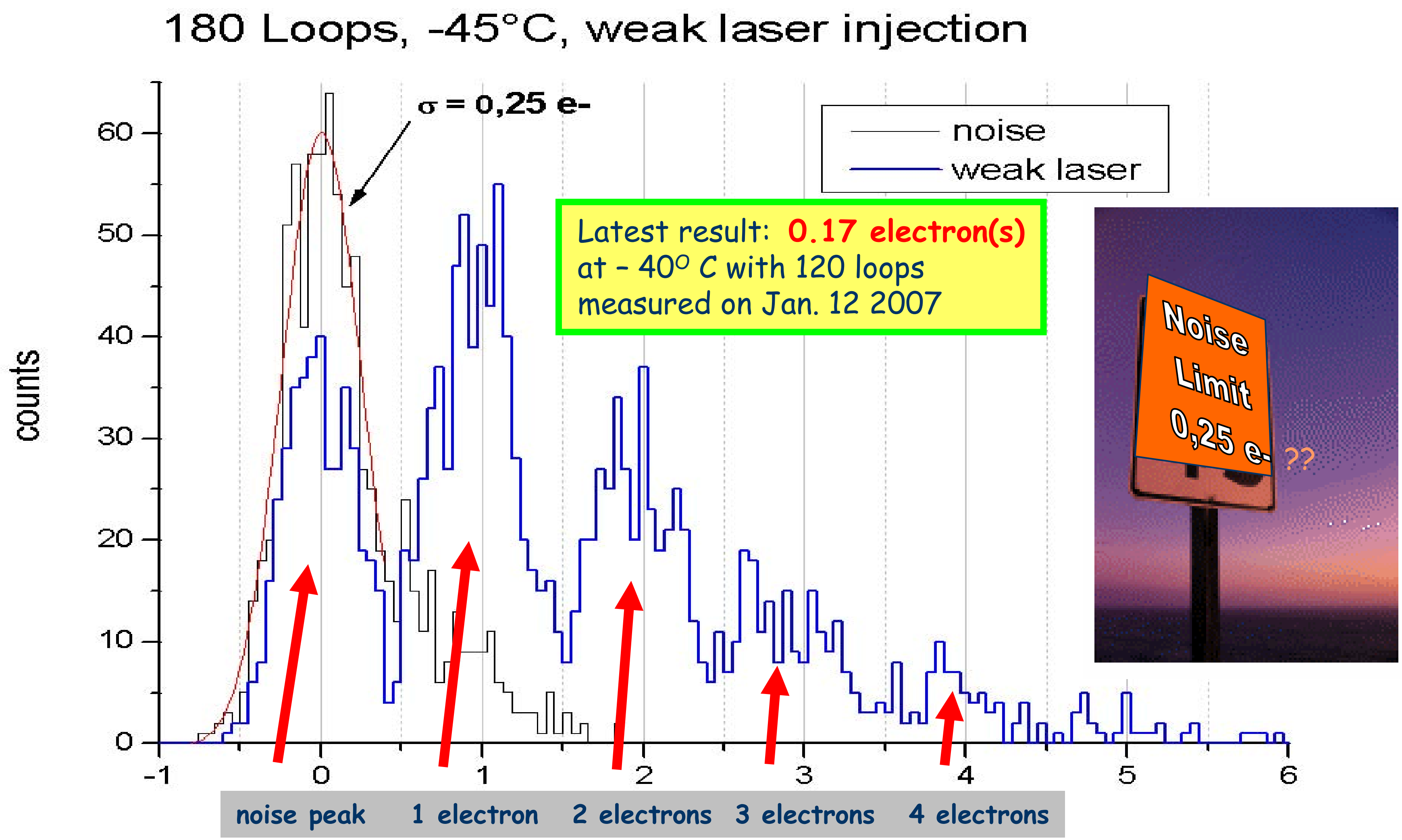
RNDR tests: noise and very low level laser light

- Fit to noise peak: 0,25 elecrons rms
- Distinct peaks for 0, 1, 2, ... electrons



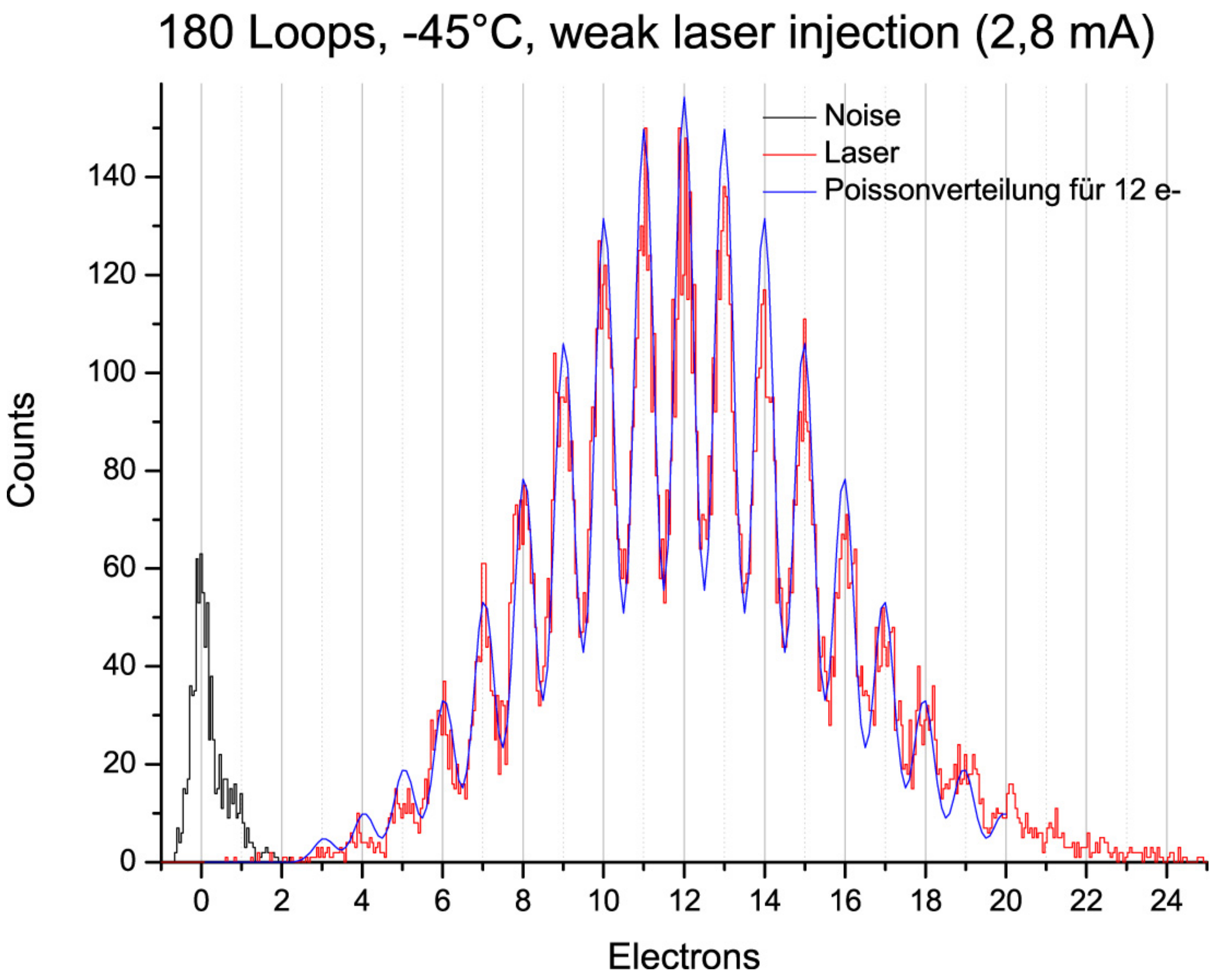
Poisson distributed photons

- Fit to noise peak: 0,25 elecrons rms
- Distinct peaks for 0, 1, 2, ... electrons



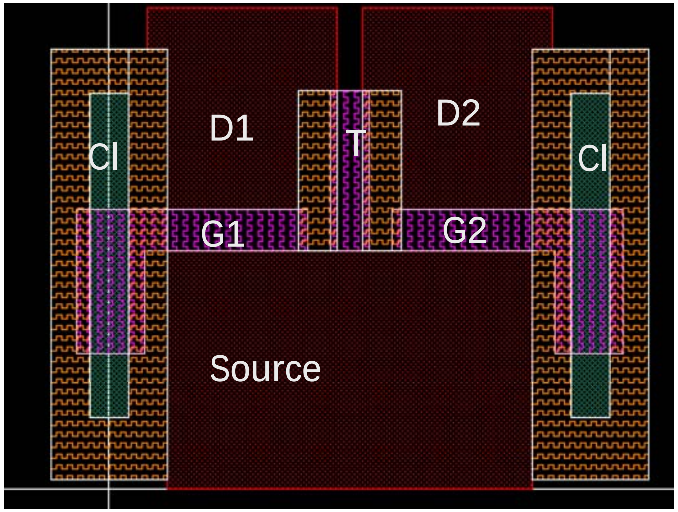
RNDR tests: low level laser light

- Low number of electrons created by laser pulse
- Good separation between peaks
- Poisson distribution smeared with Gaussian fits data very well
- High energy tail of noise peak (due to leakage current) not yet taken into account properly

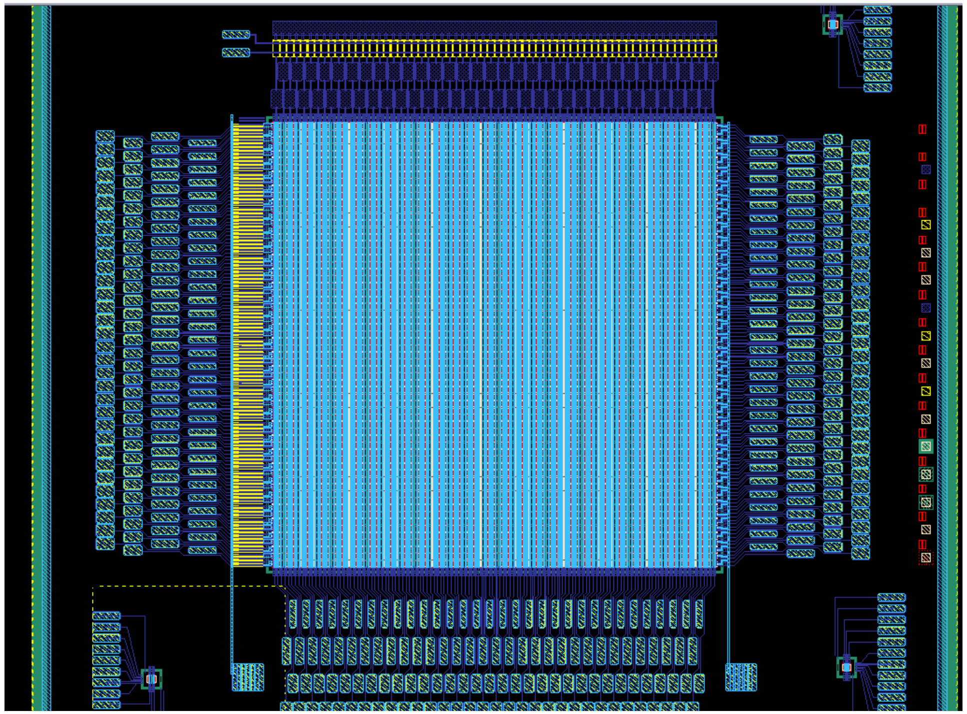


RNDR readout: further activities

- Next generation devices:
  - Double DEPFETs with three transfer gates allowing transfer with both DEPFETs drawing current
  - Larger pixel matrices: 64x64 devices in production
- Readout with differential amplifiers
- Readout chip for matrix readout



Linear double DEPFET structure with common source and three transfer gates



Layout of 64x64 RNDR DEPFET matrix with 75x75 μm^2 pixel size

Avalanche Detectors

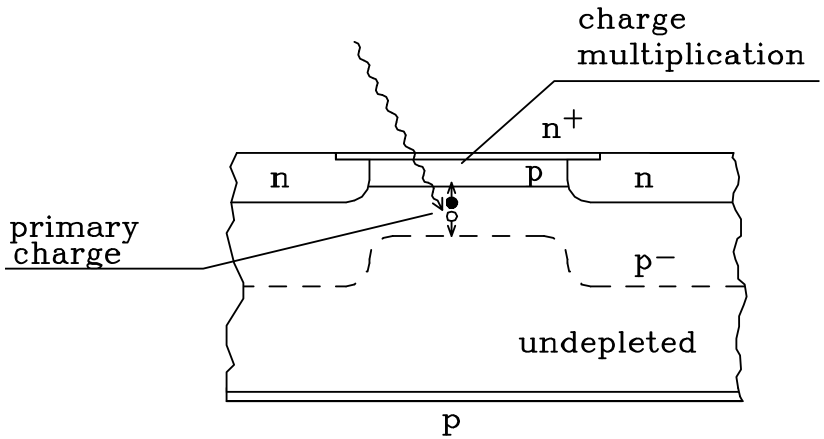
Avalanche diode

Charge multiplication in high electric field region:

- Electrons and holes are accelerated by electric field in between collisions (with lattice defects)
- Are able to create electron hole pairs if they require enough energy
- Electrons are slightly more likely to create pairs than holes
- Multiplication probability is very strongly dependent on electric field strength

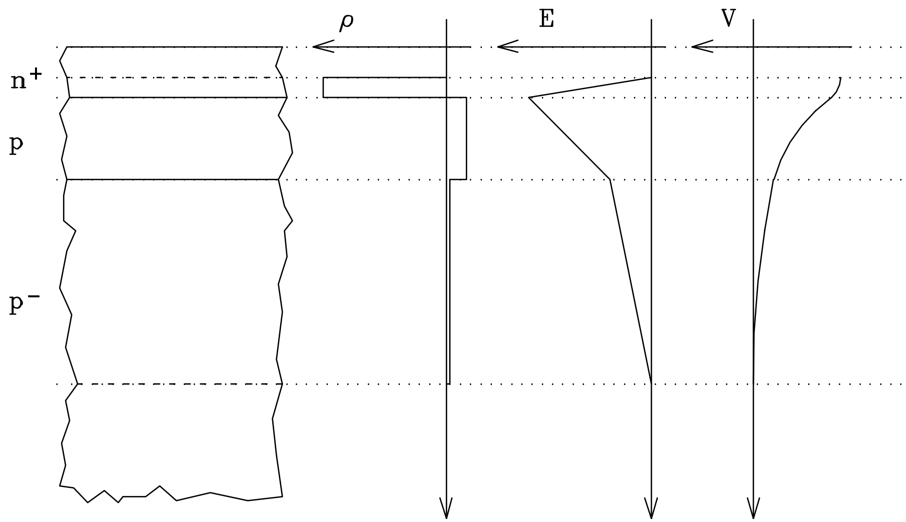
Operation regimes:

- Proportional regime: (essentially) only electrons are multiplying
- Breakdown regime: both carrier types multiply. Current has to be limited by external means (limited Geiger mode)



Area device :

- Bulk is only partially depleted
- Non homogeneous high field region
- Entrance window obstructed
- Can be operated in proportional or limited Geiger mode



Desired topology (for good efficiency):

- long and homogeneous high field region
- Avalanche initiated by primary electron (not hole)
- Non obstructed radiation entrance window

Avalanche Drift Diode

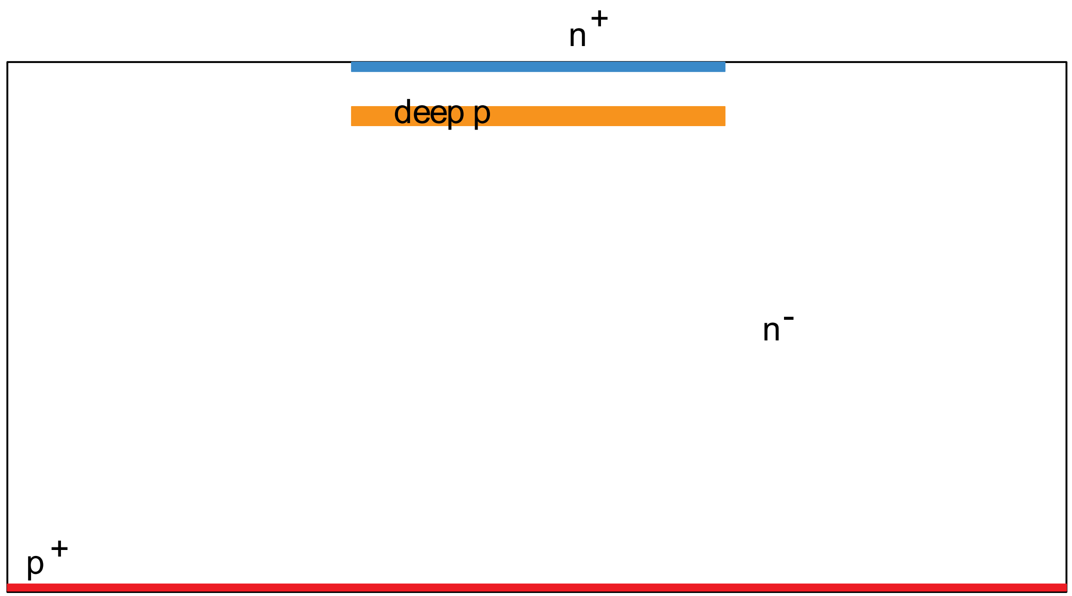
The new avalanche amplification concept

- Basic idea:
  - Should be compatible with our fully depleted detectors:
    - PN-CCDs
    - Silicon Drift Diode
  - with radiation entrance on backside of fully depleted device
  - Focus signal electrons on (small) avalanche region

- Development of concept to be shown in several steps

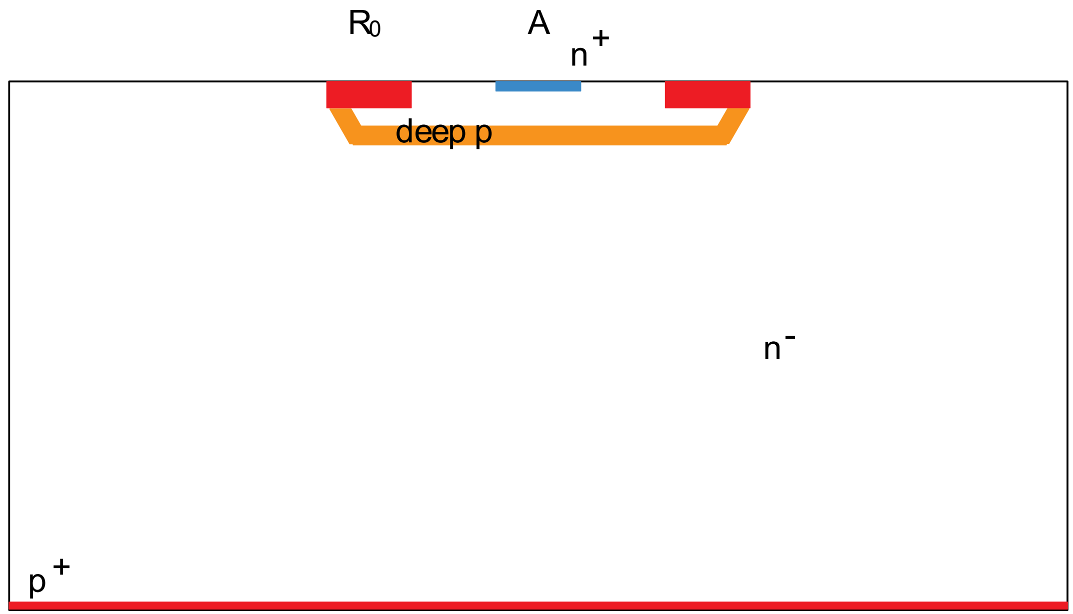
Development of concept I

- Fully depleted bulk radiation entrance on backside
  - Adjustment of field needs large voltage variation



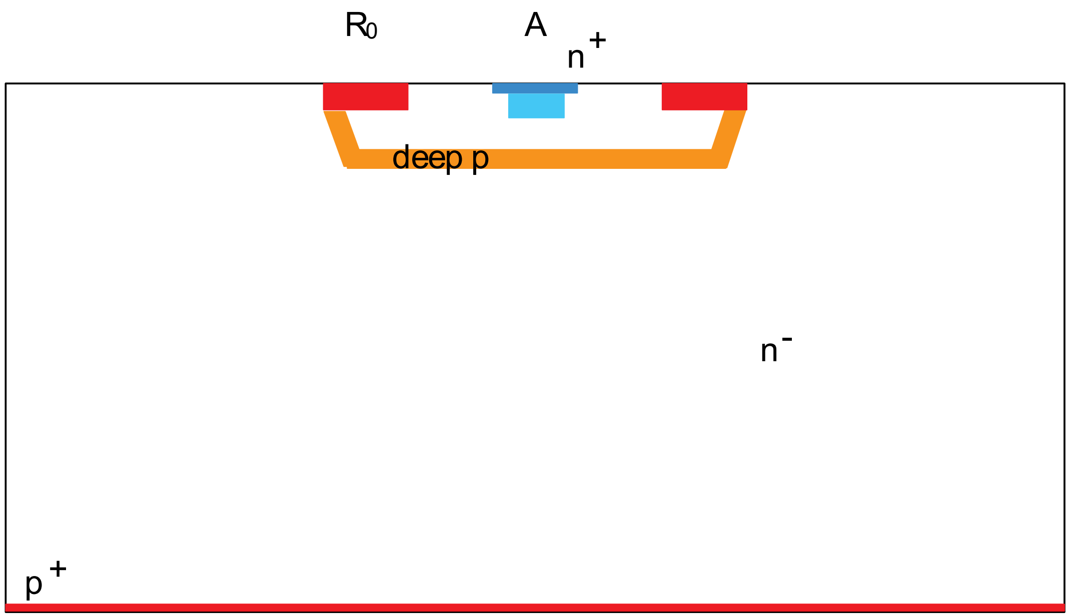
Development of concept II

- Fully depleted bulk radiation entrance on backside
- Biasing from top ring-like structure
  - Gives better control of high field region



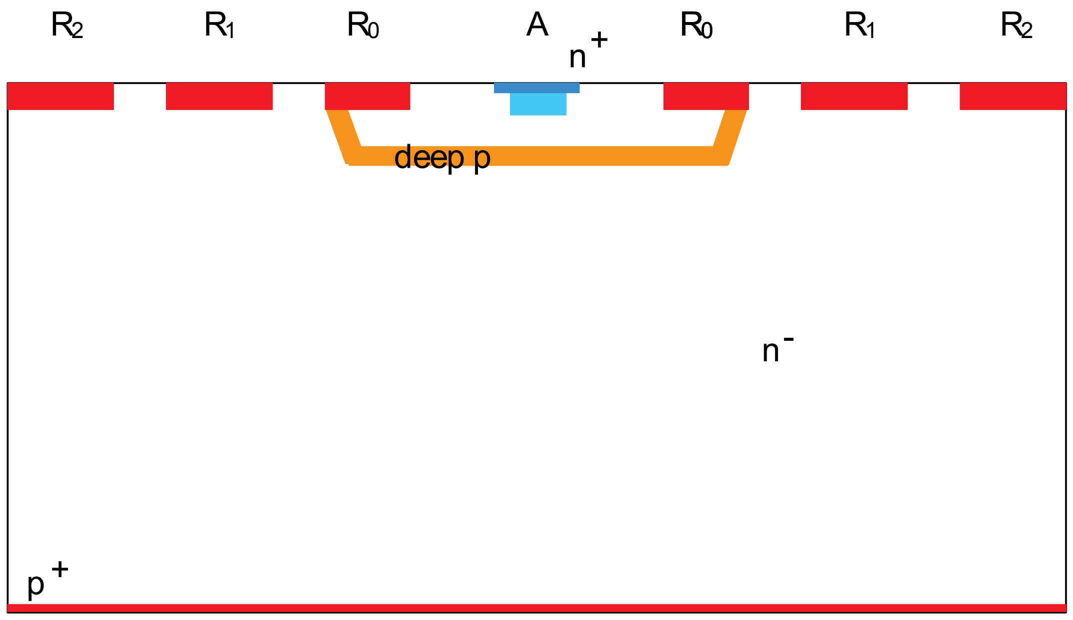
Development of concept III

- Fully depleted bulk radiation entrance on backside
- Biasing from top ring-like structure
- Increase depth of buried p-layer ; add deep n implant to
  - Confine high field region to centre
  - Depletes buried p-layer in centre only
  - Prevents field peaks at edges



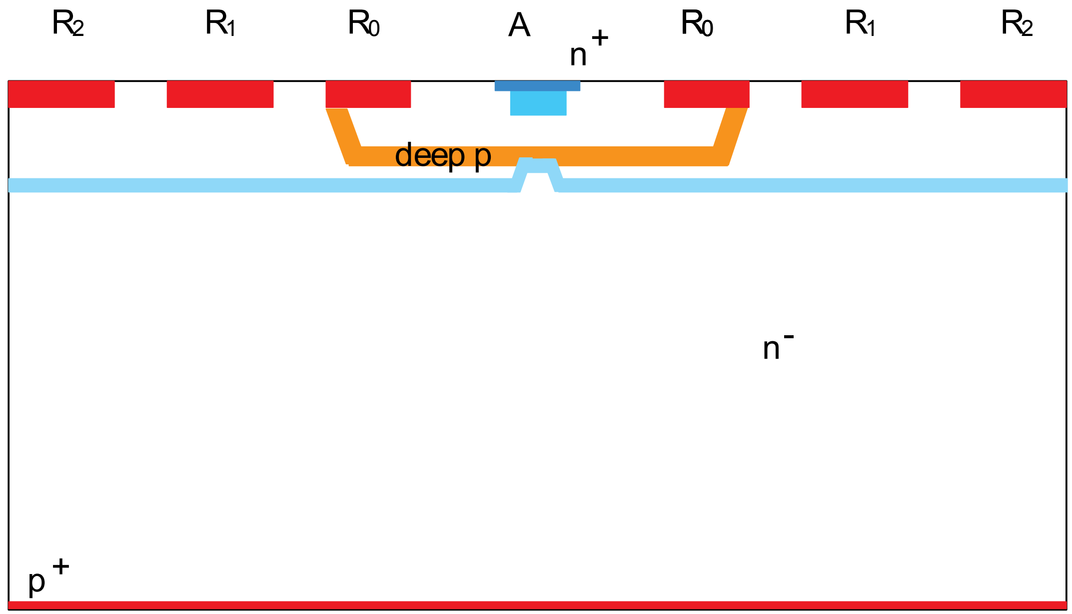
Development of concept IV

- Fully depleted bulk radiation entrance on backside
- Biasing from top ring-like structure
- Deep n implant in centre
- Addition of drift rings
  - Focusses electrons to avalanche region



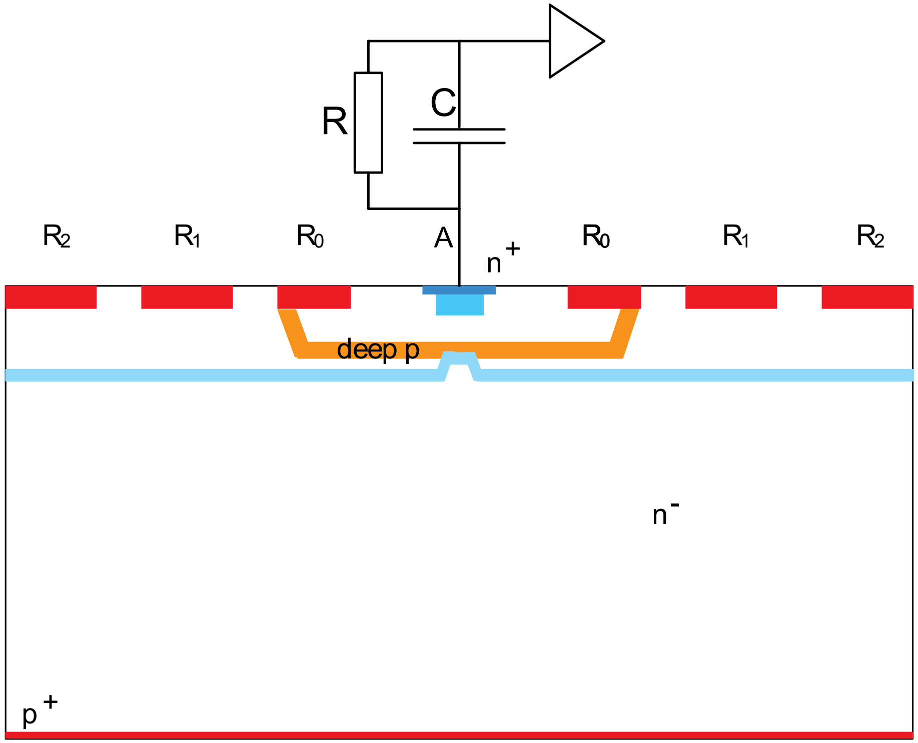
Development of concept V

- Fully depleted bulk radiation entrance on backside
- Biasing from top ring-like structure
- Deep n implant in centre
- Addition of drift rings
- (modulated) Buried n layer
  - Prevents hole emission to backside
  - Focusses electrons to centre of avalanche region



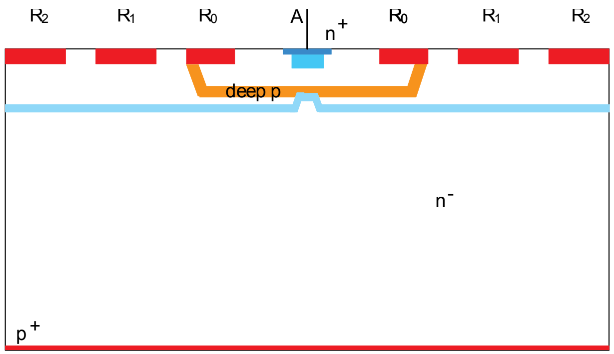
Limiting in Geiger mode operation

- Reduce voltage across high field region after firing



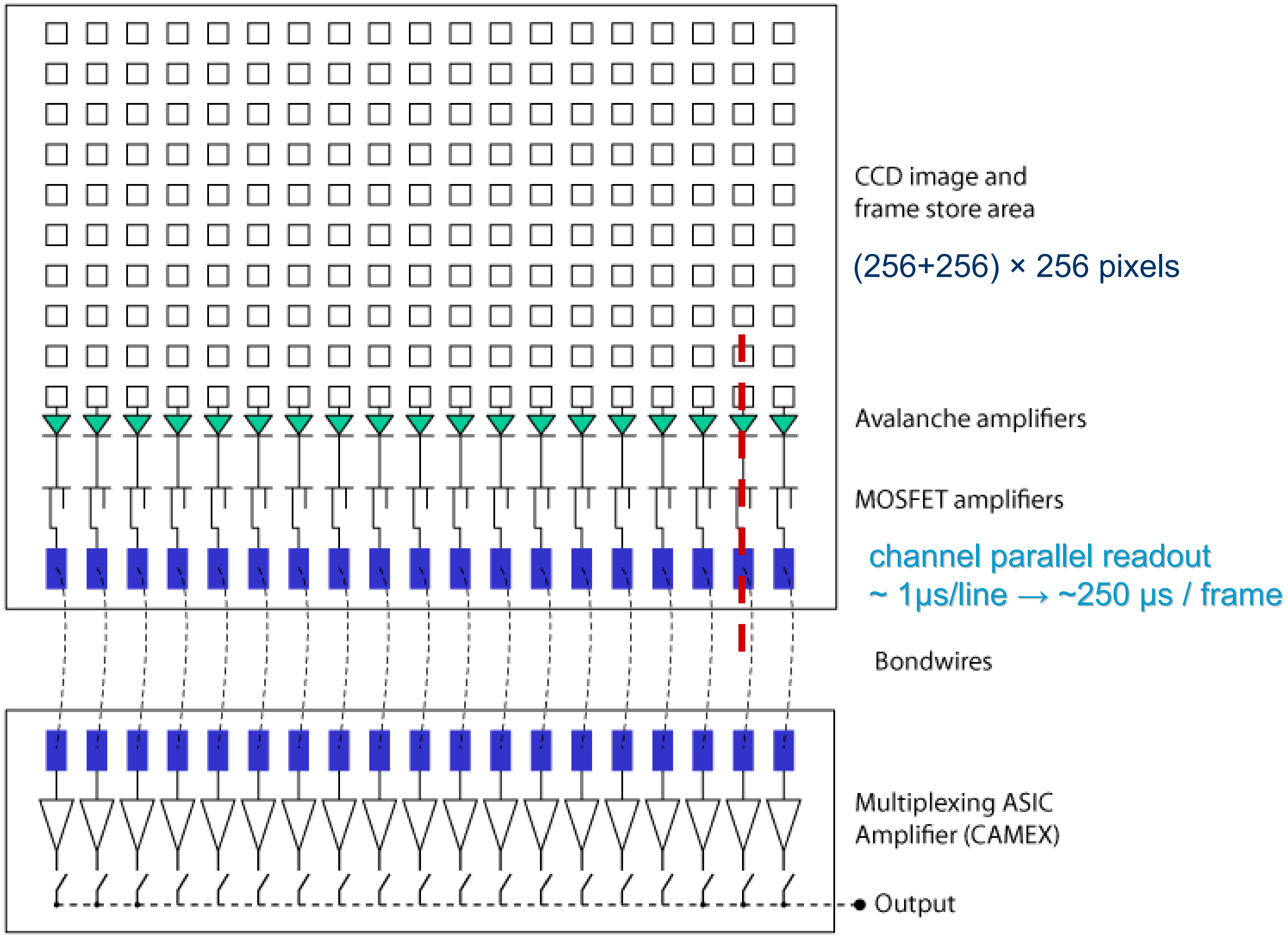
- Passive elements (resistor and capacitor) integrated into detector

Application of new avalanche structure concept

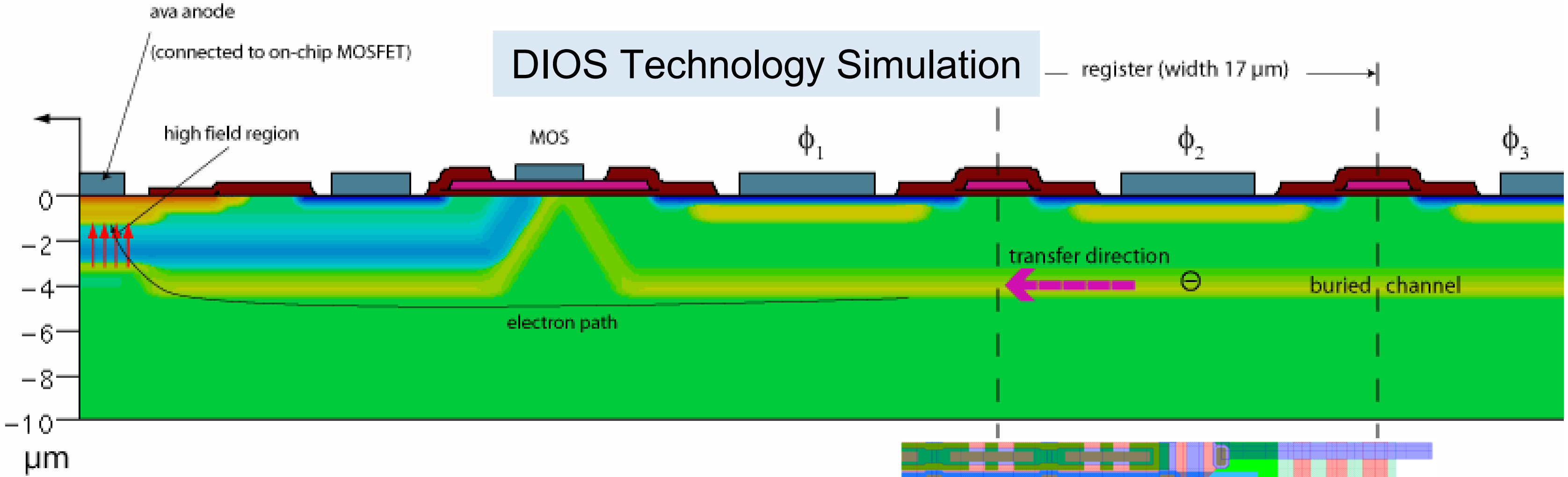


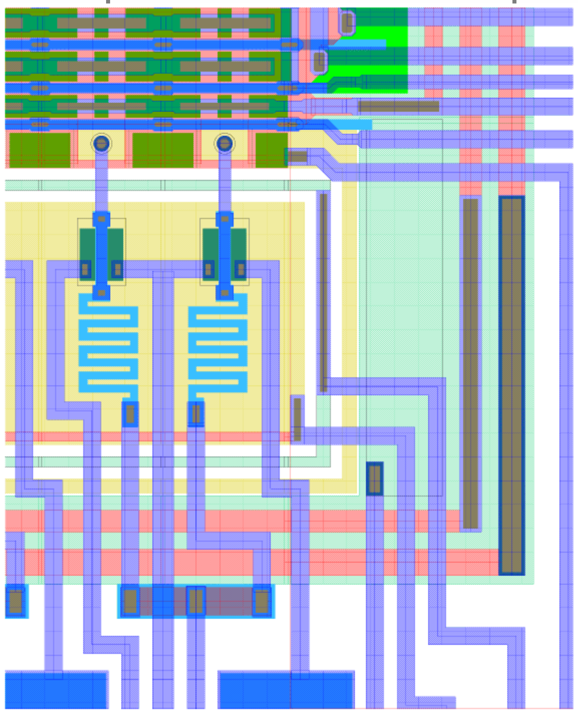
- As central element in Avalanche Drift Diode (Combination of Drift diode with avalanche amplifier)
- Avalanche Drift diode array working in limited Geiger mode as backside illuminated „Silicon Photomultiplier“
- As readout element of pnCCD for single electron detection

Avalanche CCD Schematics



CCD with Avalanche Diode Readout: Technology Simulation





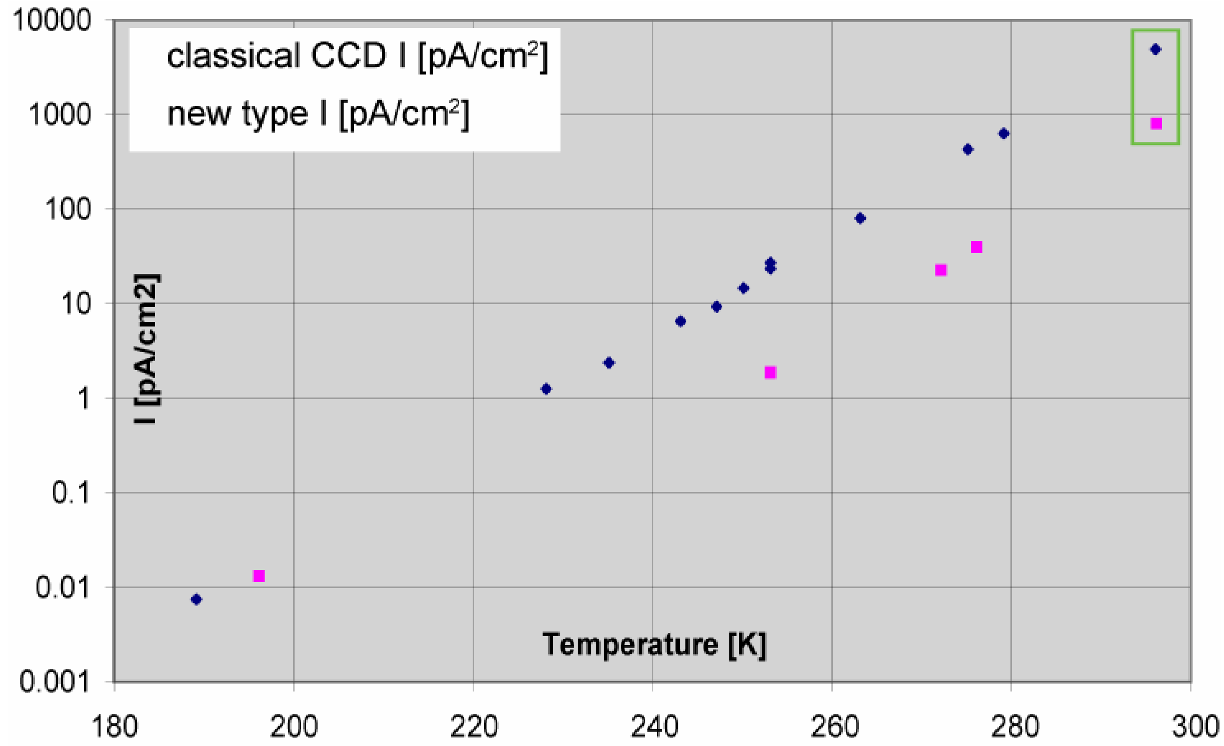
- MOS Source follower integrated into same chip
- Production together with Backside Illuminated „Silicon Photomultipliers"

Very Low Background Single (Optical) Photon Detectors

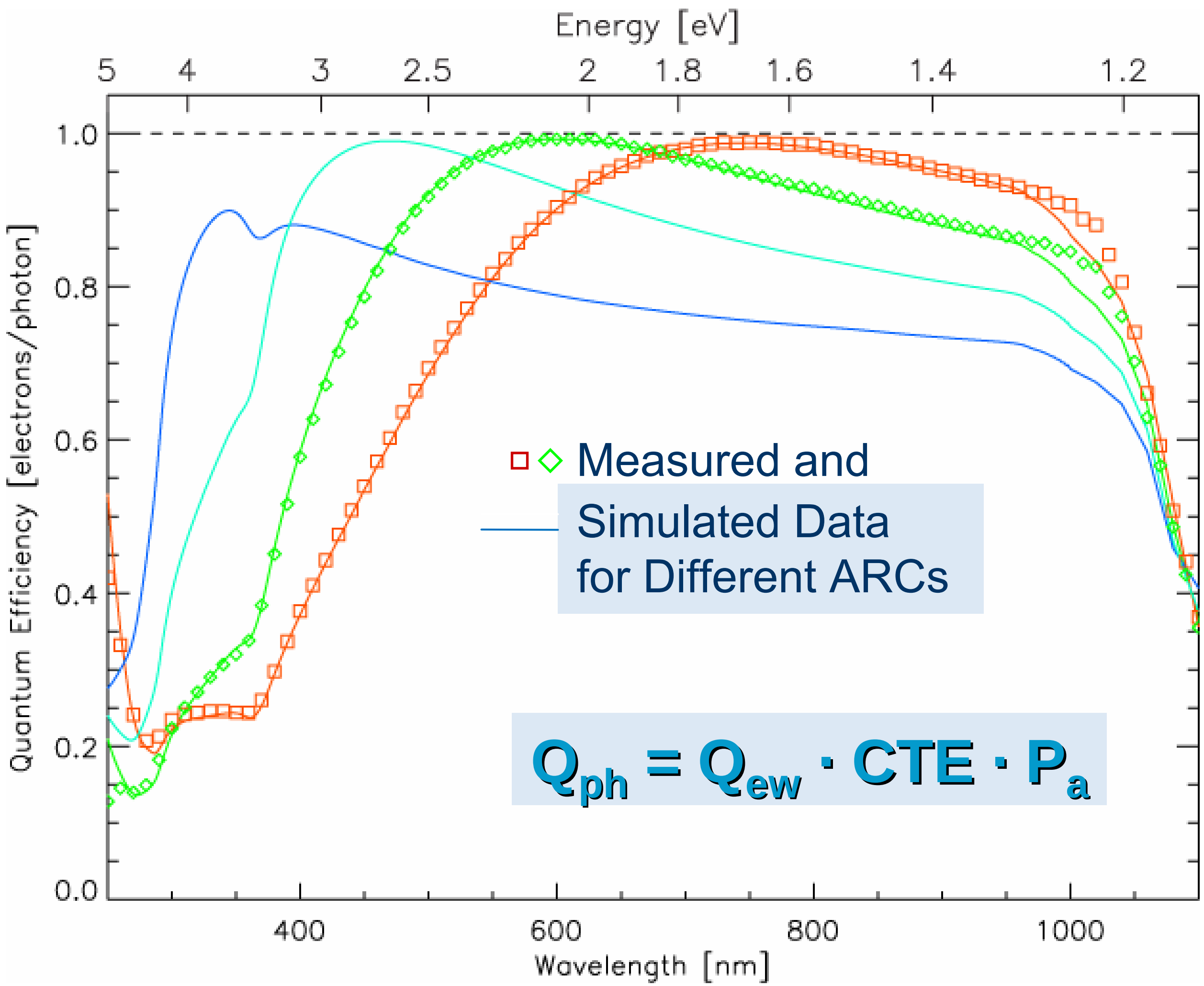
Single electron background

- Dominant source: thermal generation of electron-hole pairs
- Can be reduced by cooling
- Measured temperature dependence of leakage current

- For 10mm2 and 190K 1hour one obtains 2×10^7 electrons
- Reduction by an order of magnitude every 20K



Entrance Window of Back Illuminated Devices



Background estimates

- Single electron background rates
  - Assumptions:
    - Image area size $10mm^2$
    - Temperature 130K -> scaling from measured value at 190K 10^{-14} A leakage current 10^{-14} x 10^{-3}A/cm^2 = 10^{-17}A
    - Pixel size 100x100 μm^2 ->1000 pixel in image area
    - Readout rate 1 frame/second
  - Dark rate in image region
    7 el/s or 2×10^4 el/hour in 10 mm^2 area
  - Dark rate in pixel
    7×10^{-3} el/sec or 2 el/hour
- Double electron background rate
  - Probability of collecting 2 electrons in same pixel of $10mm^2$ area
    7 x $7 \times 10^{-3} = 5 \times 10^{-2}$ double electron events/s = 140 /hour

Scaling of Estimated Background Rates

Background rate scaling: events/hour in Image area

	Single electron background rates	Double electron background rates
Leakage current (I) (Temperature)	I	I^2
Image area (A)	A	A
Pixel area (P)	1	P
Charge collection time (tcoll)	1	tcoll

Single photon sensitive detectors

- PnCCDs with avalanche readout
  - Cannot distinguish 1 from 2 electrons
- PnCCDs with RNDR (ping-pong) readout
  - Can measure the number of electrons collected in each pixel
  - Setting threshold to two electons would almost completely remove the background
  - This would eliminate sensitivity below approx. 3eV

- Detector development will be done for astrophysics application
- requires large effort in terms of time manpower and finances

Thanks to my friends in the
MPI Semiconductor Laboratory who have provided much of the material I had the priviledge to present at this workshop

Summary

THE END