TCAD simulations on DEPFET sensors at the MPG Halbleiterlabor

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MAX PLANCK SEMICONDUCTOR LABORATORY

Outline

- Introduction
- 2D simulations of DePFET
  - interesting characteristics
  - comparison with measurements
  - study of possible improvements
- 3D simulations of Quadropix DePFETs
  - optical polarimetry
  - Quadropix concept
  - comparison of measurements and simulations
  - device optimization

MPS Semiconductor Laboratory (in German: MPG Halbleiterlabor - HLL)

MAX PLANCK SEMICONDUCTOR LABORATORY

At present @ Siemens Campus Neuperlach Munich

- 1000m² of clean room area
- 330m² of ISO3 area
- Full 6 inch silicon process line

From mid 2023 @ IPP Campus Garching

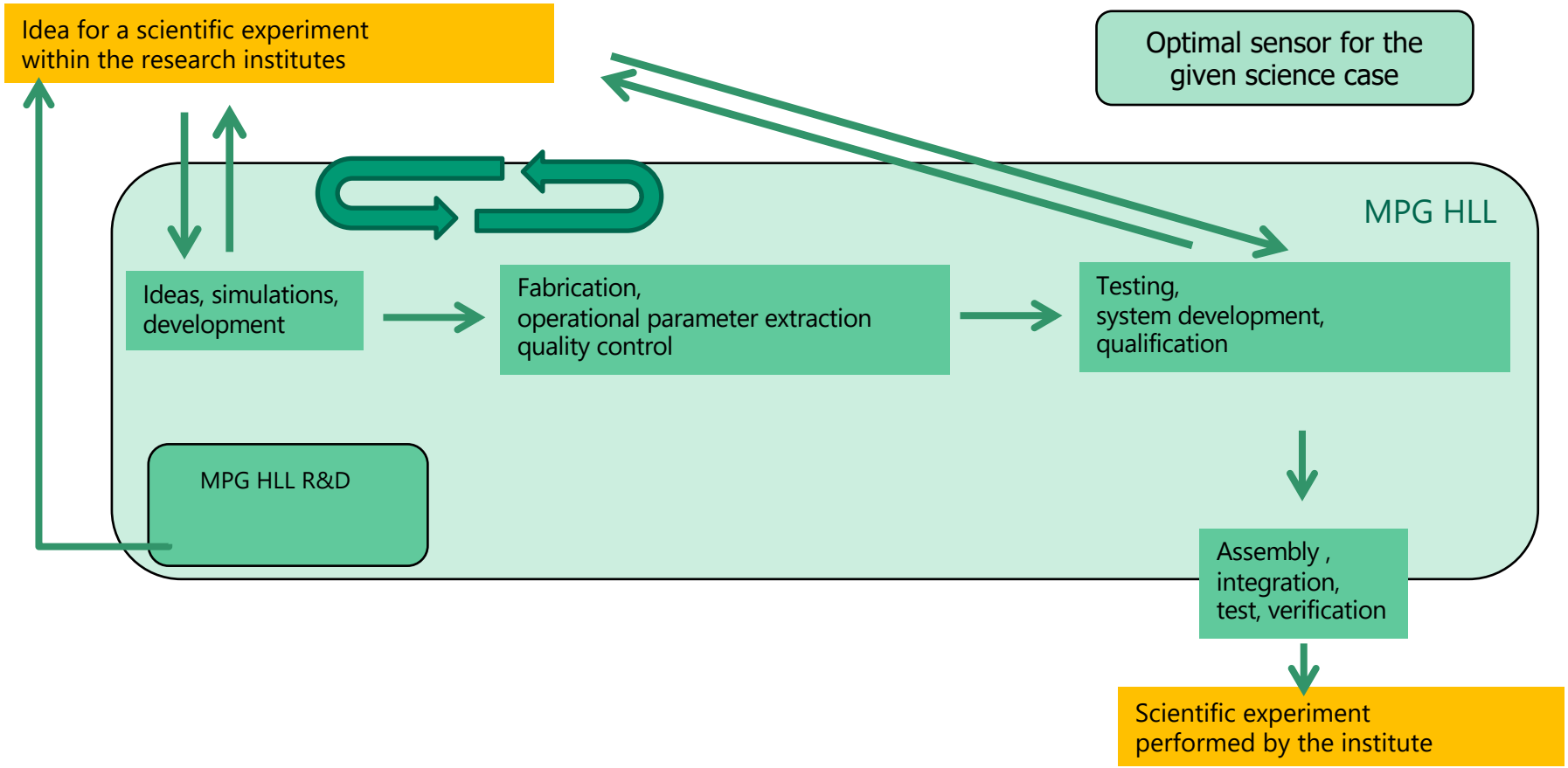
- 1500m² of clean room area
- 600m² of ISO3 & ISO4 area
- 8 inch silicon process line

New building in mid 2021

From 2023 HLL will be part of Munich Quantum Valley

Central facility of the Max Planck Society
with 40 employees: scientists, engineers and technicians + guest scientists, engineers and students

MPG HLL in a nutshell



DePFET - some project and application examples

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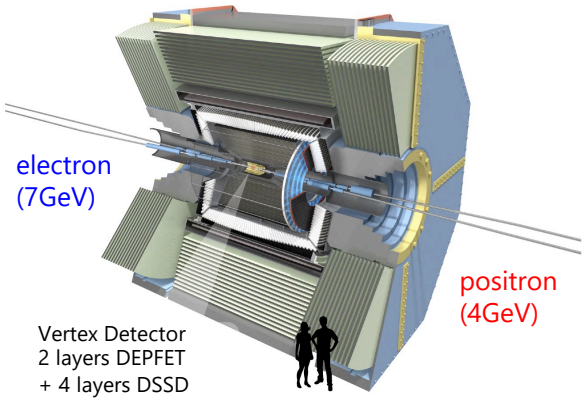
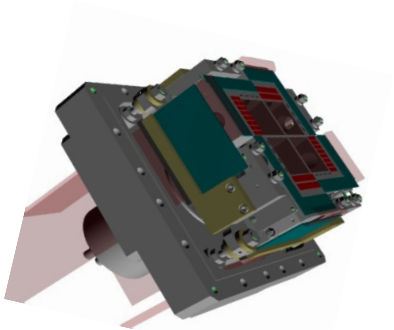
DePFETs at KEK - Japan



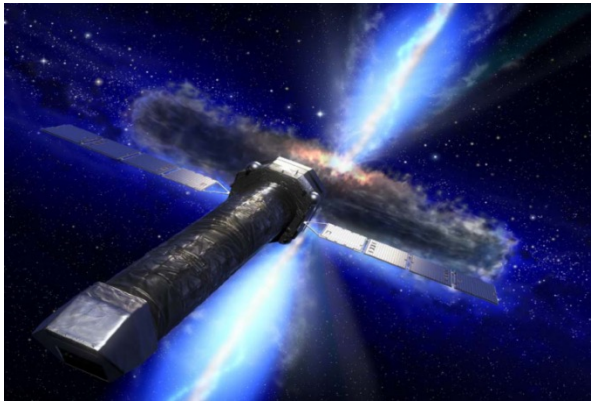
particle tracking

EDET



direct electron detection @TEMs

WFI aboard Athena

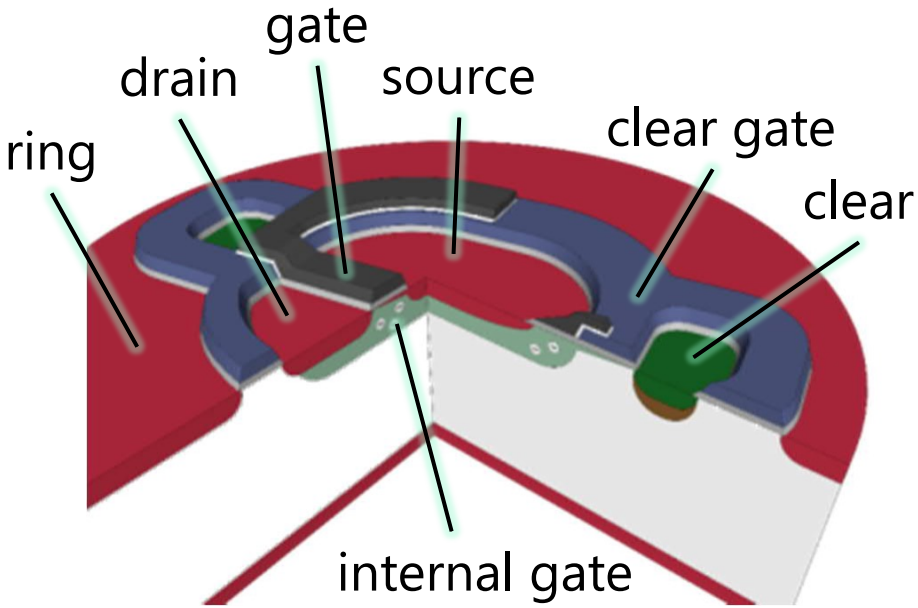


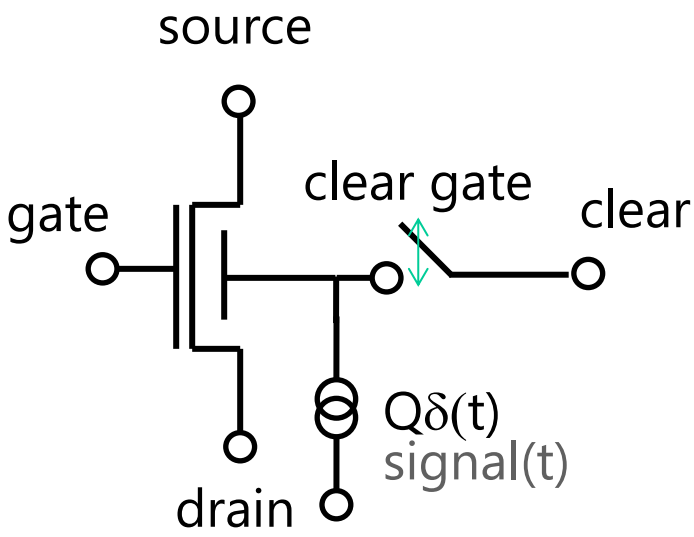
Nandra et al. 2013, arXiv:1306.2307

X-ray imaging spectroscopy

We also produce
-SDD (silicon drift detectors)
-pnCCDs
-Avalanche Diodes
-etc.

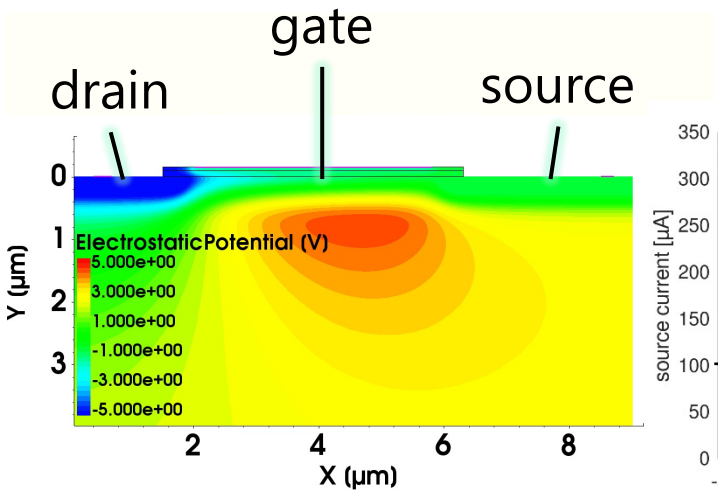
The DePFET

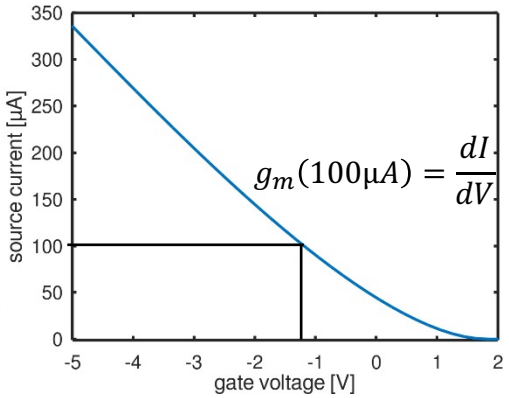

gate
drain
source
ring
clear gate
clear
internal gate


source
gate
clear gate
clear
Qδ(t)
signal(t)
drain

2D simulation flow

Process Simulation → Electrical Simulation → I-V characteristics operation point





Signal Response

charge gain (current readout)
gain (source follower)

Noise

at the moment only white noise

Impact Ionization

cause additional electrons in the internal gate

Comparing Measurements and Simulations – 2D

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Measurements on Athena prototype DeFPETs
different technology, different geometry

	Tn-1	Tn-2	Tn-3	Tn-4	Tk-1	Tk-2	Tk-3	LG1	LG2	LG3	LG4
Source	[2]	[2]	[2]	[2]	[2]	[2]	[2]	[3]	[3]	[3]	[3]
Technology	Thin Halo	Thin	Thin	Thin Plasma	Thick	Thick	Thick Plasma	Thick	Thick	Thick	Thick
W/L	20/5	20/5	20/5	24/5	20/5	20/5	24/5	20/5	24/4	24/4.5	24/5
Measured											
$g_m(100\ \mu A)$ **[µS]**	64.6	64.94	64.45	70.18	48.75	48.74	49.47	50.3	66.5	60.3	57.5
Gain [µV/e]	6.2	5.95	5.66	4.86	8.06	8.28	6.75	8.19	8.98	7.69	6.88
@ current [µA]	100	100	100	100	177	199	188	133	221	188	155
ENC	2.2	2.44	2.38	2.69	1.95	2.04	2.18	1.95	1.95	2.09	2.22
2D Simulation											
$g_m(100\ \mu A)$ **[µS]**	69.39	65.89	65.89	69.51	53.98	53.98	53.46	53.98	63.78	61.26	59.38
Gain [µV/e]	5.75	5.42	5.42	4.47	8.04	7.94	7.38	8.18	8.47	7.60	6.94

Δg_m %	7.41	1.46	2.23	-0.95	10.72	10.75	8.06	7.32	-4.09	1.59	3.27
$\Delta Gain$ %	-7.26	-8.91	-4.24	-8.02	1.49	-1.21	9.33	-0.12	-5.68	-1.17	0.87

W. Treberspurg et. al, "Measurement results of different options for spectroscopic X-ray DEPFET sensors", JINST 13, P09014, 2018
W. Treberspurg et. al "Layout options of spectroscopic X-ray DePFETs", JINST 14, 2019

Comparing Measurements and Simulations – 2D - Noise

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Measurements on Athena prototype DeFPETs
different technology, different geometry

at the moment only white noise
1/f noise is not included

	LG2	LG1	Tk-1	Tk-2	LG3	Tk-3	Tn-1	LG4	Tn-3	Tn-2	Tn-4
Source	[3]	[3]	[2]	[2]	[3]	[2]	[2]	[3]	[2]	[2]	[2]
Technology	Thick	Thick	Thick	Thick	Thick	Thick Plasma	Thin Halo	Thick	Thin	Thin	Thin Plasma
W/L	24/4	20/5	20/5	20/5	24/4.5	24/5	20/5	24/5	20/5	20/5	24/5
Measured											
ENC	1.95	1.95	1.95	2.04	2.09	2.18	2.2	2.22	2.38	2.44	2.69
2D Simulation											
g_q [pA/e]	1019	741	758	763	849	626	551	709	505	505	434
i_w [pA²/Hz]	1.98	1.11	1.27	1.34	1.62	0.99	1.13	1.33	1.08	1.08	1.13
ENC_w	1,38	1,42	1,49	1,52	1,50	1,59	1,93	1,62	2,06	2,06	2,45

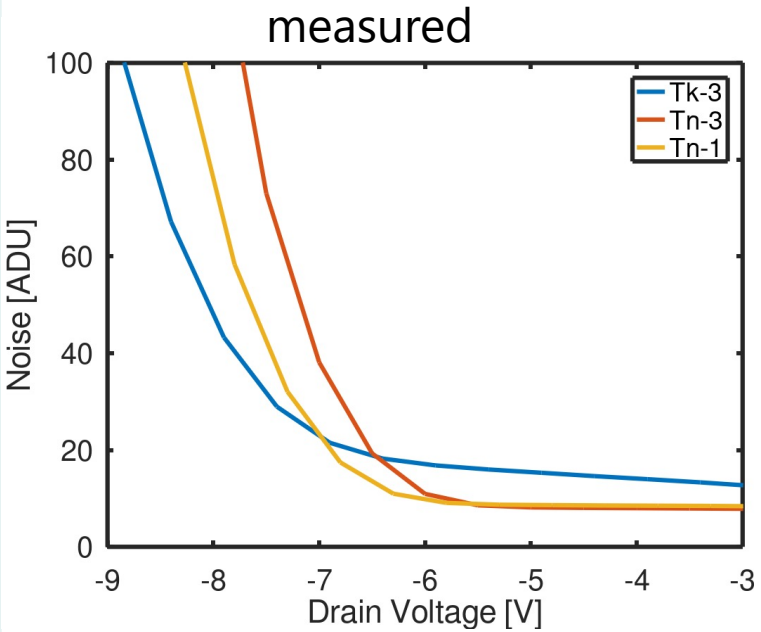
W. Treberspurg et. al, "Measurement results of different options for spectroscopic X-ray DEPFET sensors", JINST 13, P09014, 2018
W. Treberspurg et. al "Layout options of spectroscopic X-ray DePFETs", JINST 14, 2019

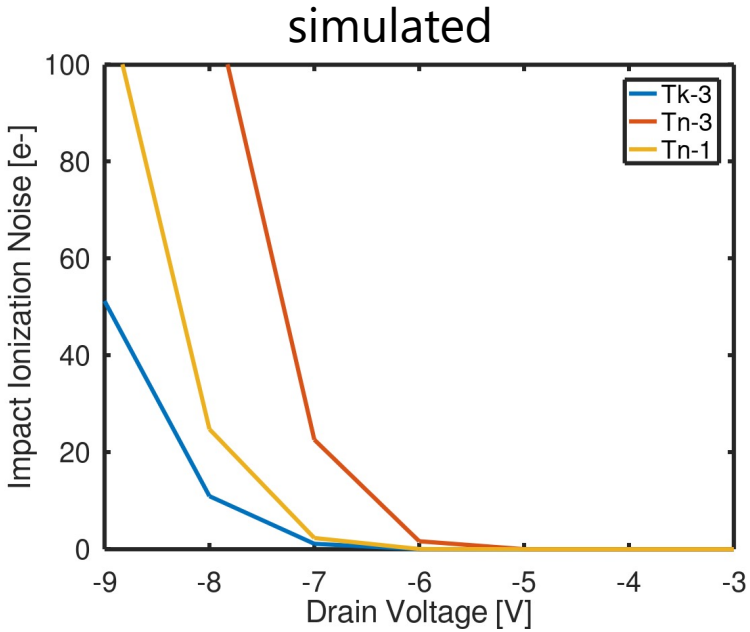
with one exception

increasing measured noise →

increasing simulated white noise →

Comparing Measurements and Simulations – 2D - Impact Ionization





good qualitative agreement of onset

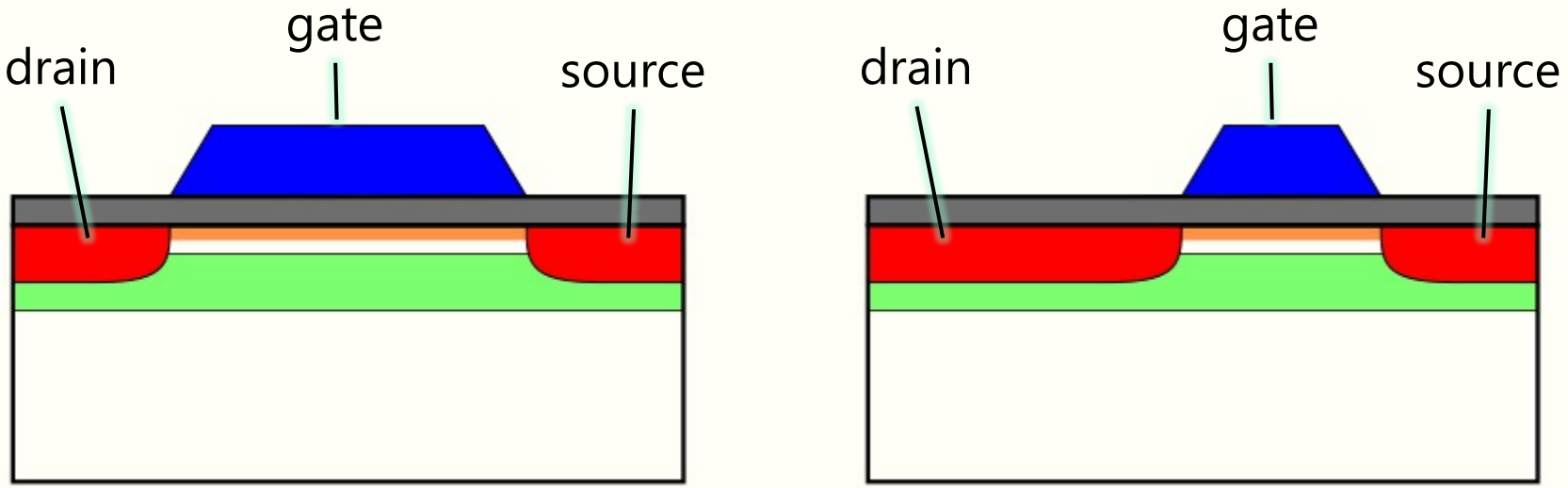
Verification of Simulations

- Measured g_m and gain met within ±10%
- Measured noise correlates with simulated white noise
- qualitative agreement of impact ionization between simulations and measurements

- overall good agreement between simulations and measurements

- utilize simulations for study of DePFET improvements

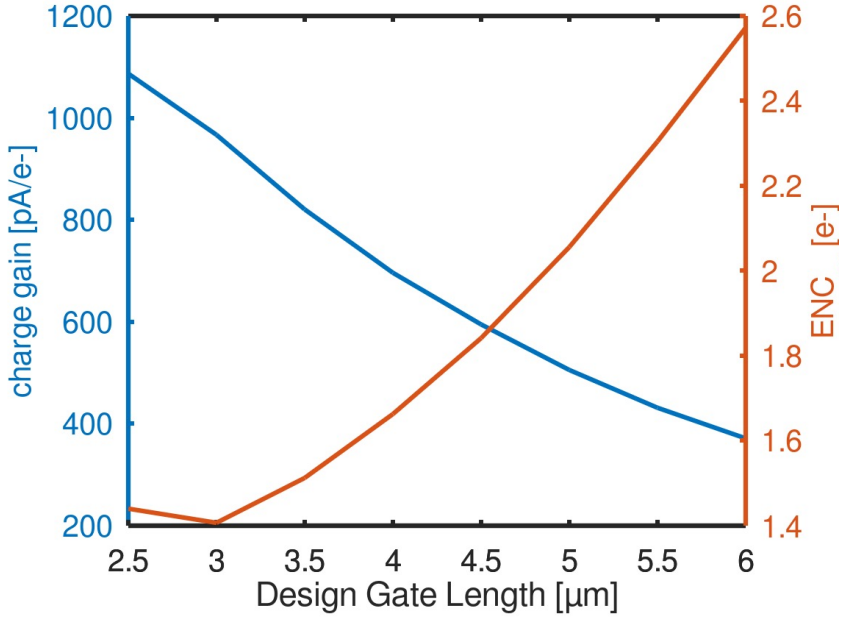
Improving the DePFET - Scaling

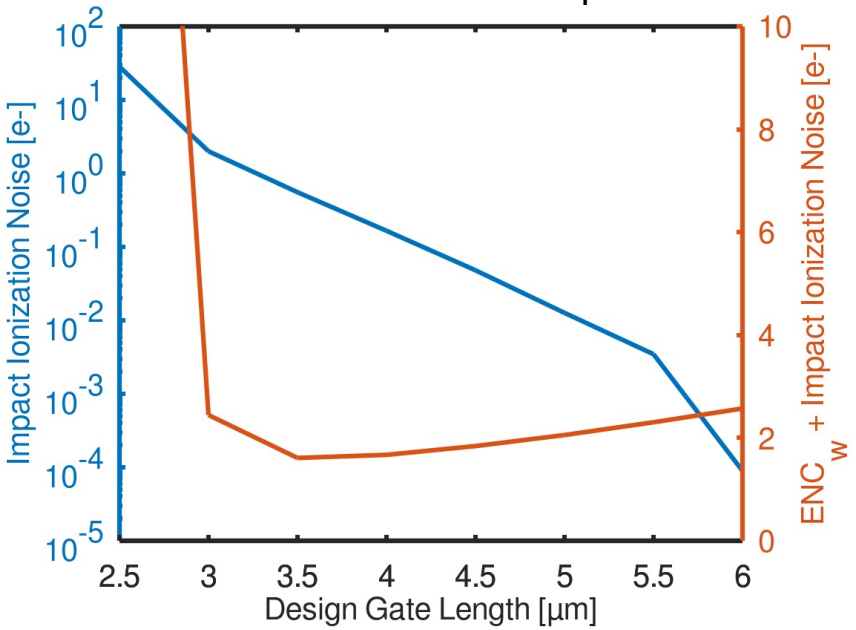


reduce gate length to minimize the
internal gate and increase charge gain

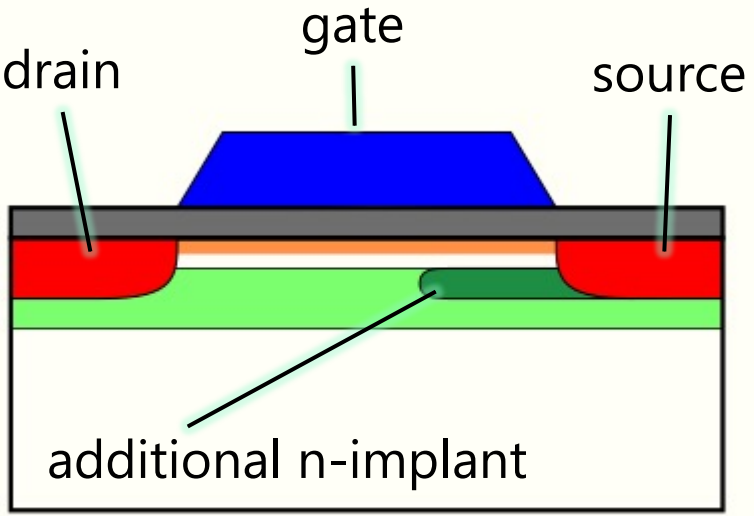
Improving the DePFET - Scaling

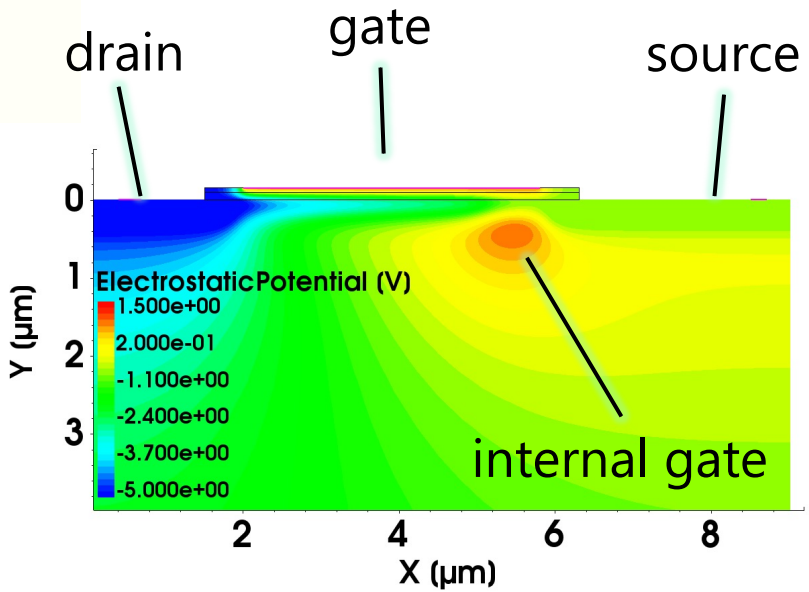
gate width of 20µm
readout time of 5 µs



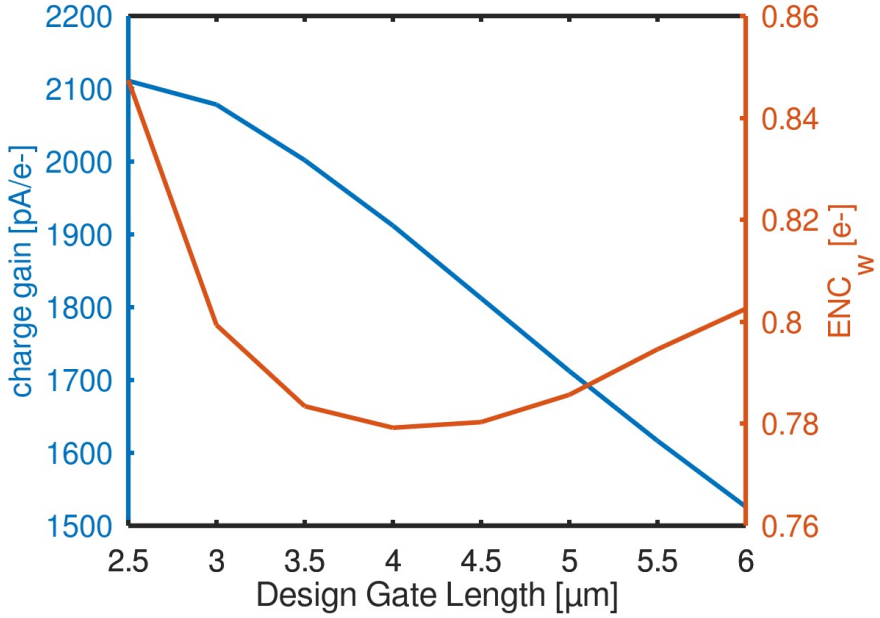


Improving the DePFET - Super g_q

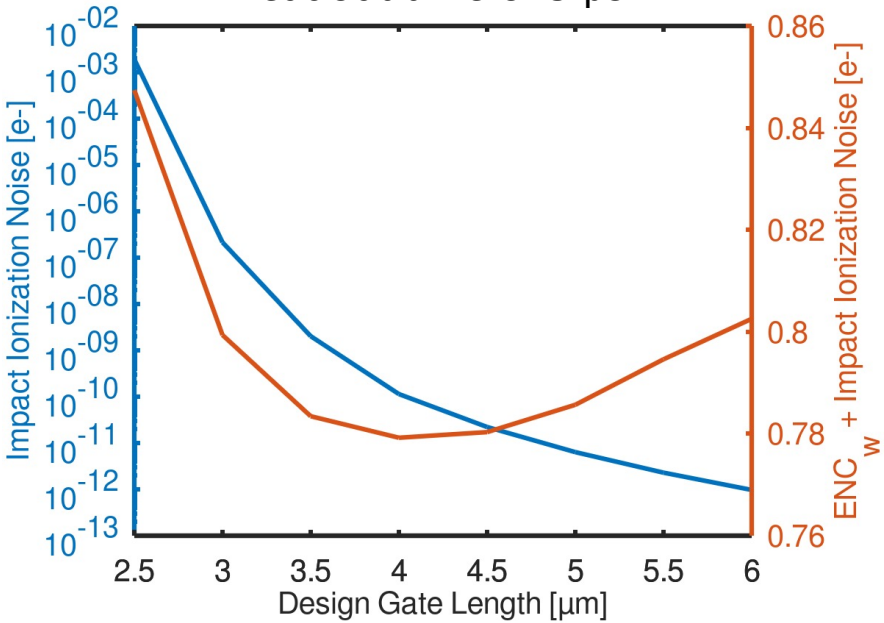




Improving the DePFET - Super g_q

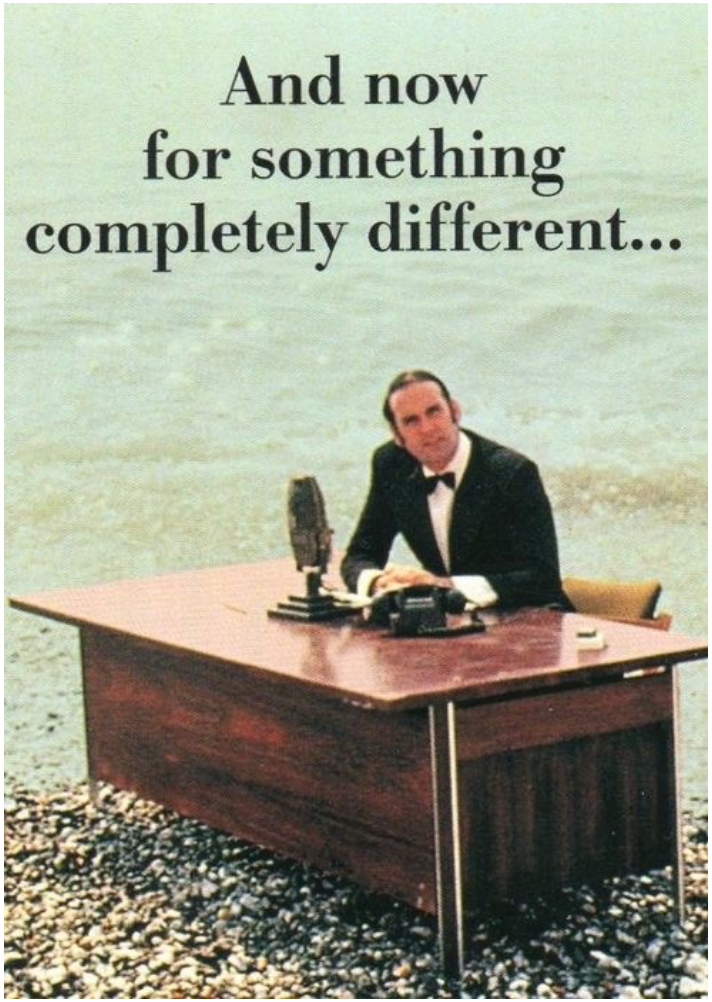


gate width of 20µm
readout time of 5 µs



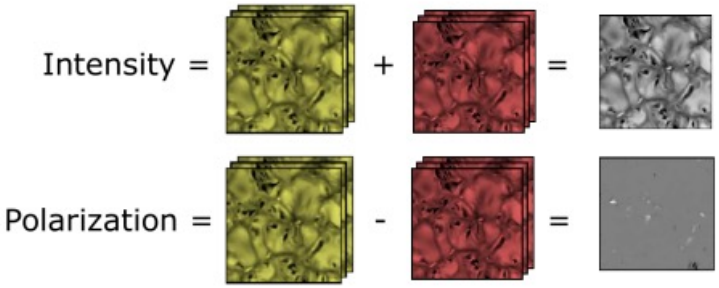
2D simulations - recapitulation

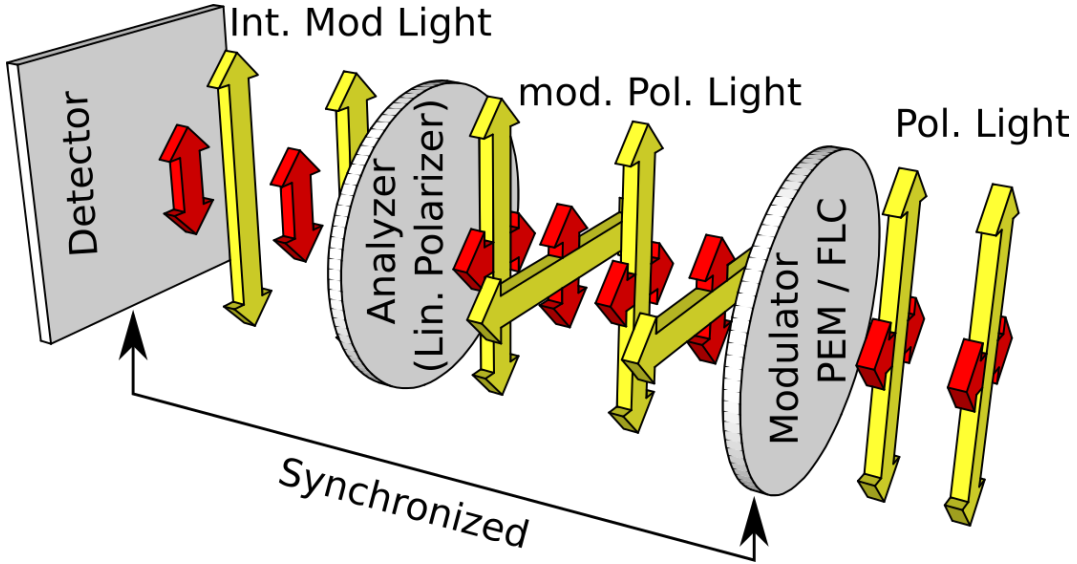
- we verified our simulations against measurements
  - ↳ overall good agreement
- we studied the effects of scaling on the DePFET
  - ↳ overall improvement but limits due to impact ionization
- we developed a new DePFET technology
  - ↳ decoupling internal and external gate size
  - ↳ improving g_q
  - ↳ reducing impact ionization


And now
for something
completely different...

Optical Polarimetry

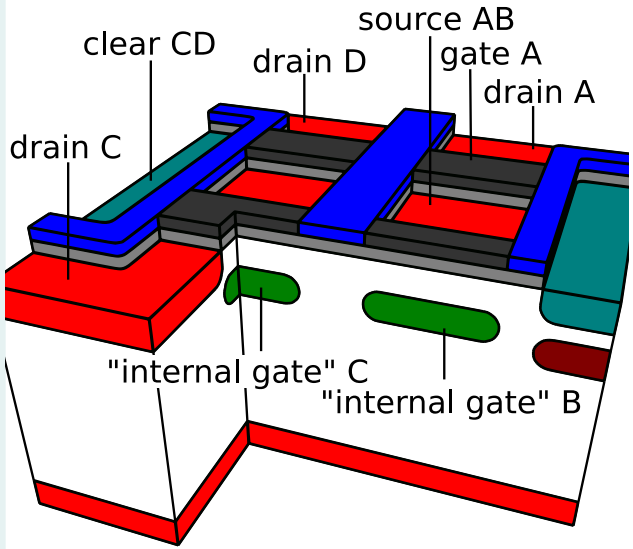
- incident light passes a modulator and a following analyzer
- modulator (e.g. piezo elastic modulator) operates at up to 50 kHz
- sensor synchronized to modulator
- generates and measures 4 different modulated intensity states,
- Stokes Parameter, I (intensity), Q, U (linear pol.) and V (circular pol.) can be calculated from the measured modulation states

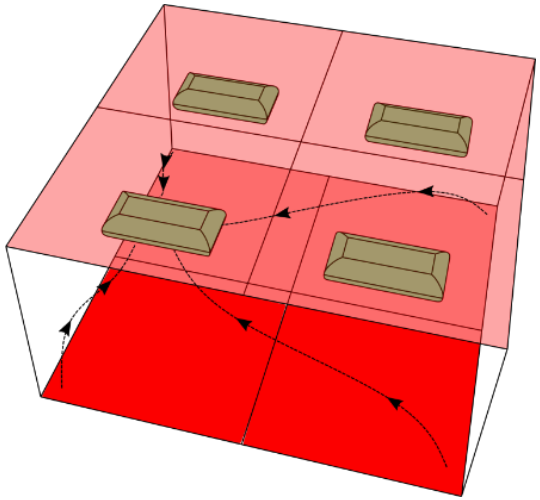


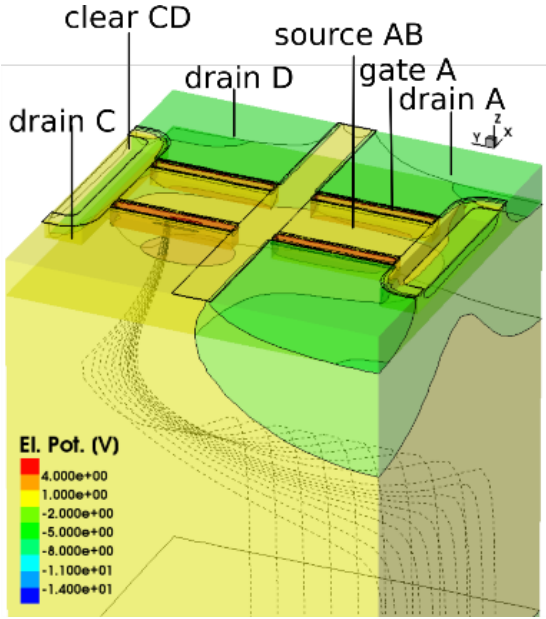


3D Simulation – Quadropix

Quadropix: combination of 4 DePFETs into a Superpixel structure
Designed for the use in fast optical polarimetry







3D Simulation – Quadropix

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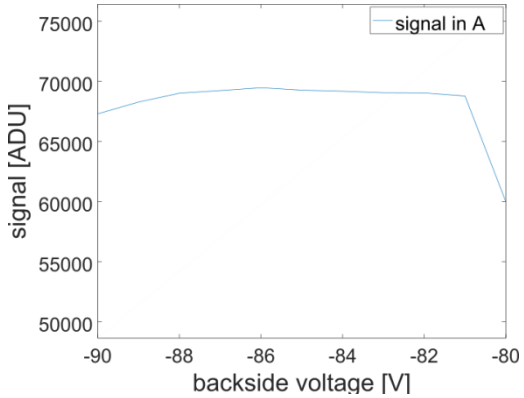
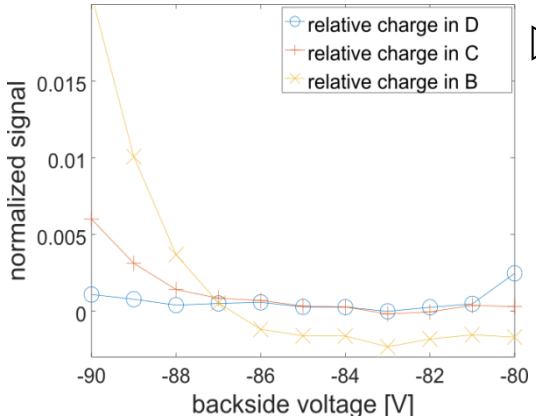
▷ measured



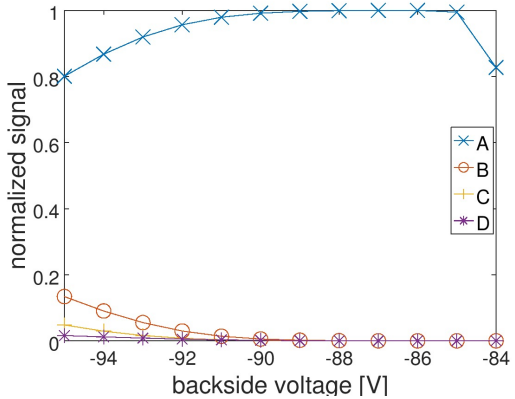
▷ depletion – 81 V

▷ losses -86 V



▷ window of 5 V

▷ simulated

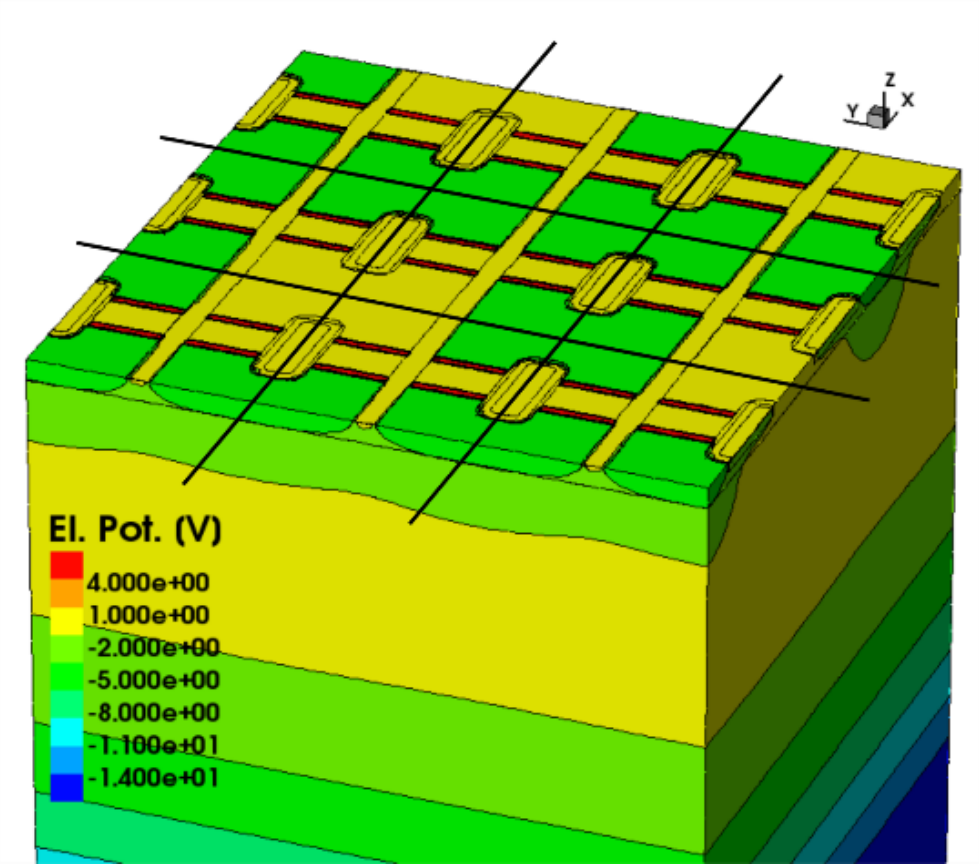


▷ depletion ~ -85 V

▷ losses ~ -90 V

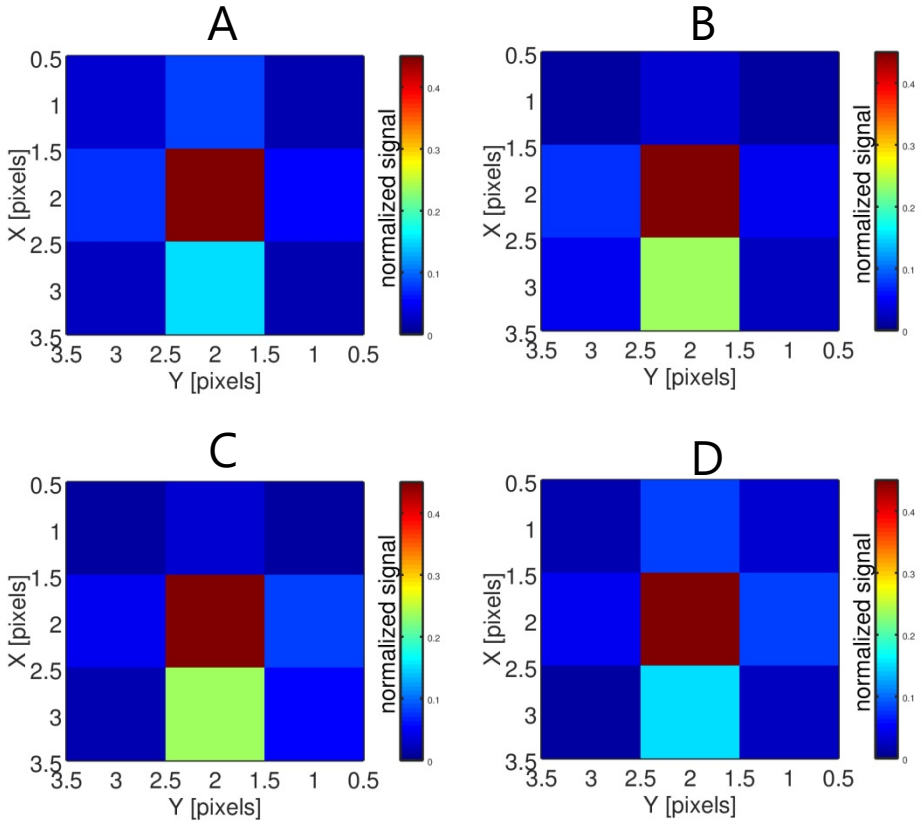
▷ window of 5 V

3D Simulation – Quadropix – assymmetric potential



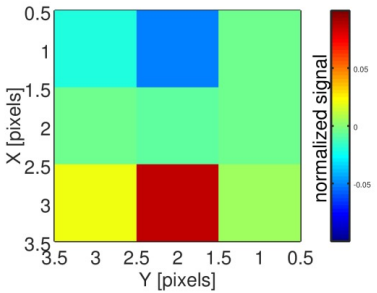
3D Simulation – Quadropix

Measured assymmetrie for injection in pixel center

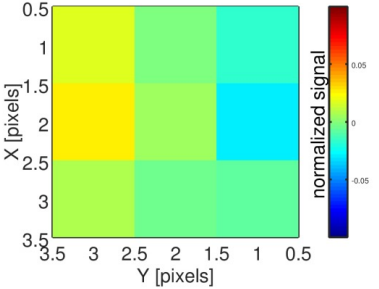


- asymmetry clearly visible
- critical as polarimetric information is obtained by subtracting images

- e.g. A-B



- e.g. A-D



3D Simulation – Quadropix – assymmetrie of charge collection

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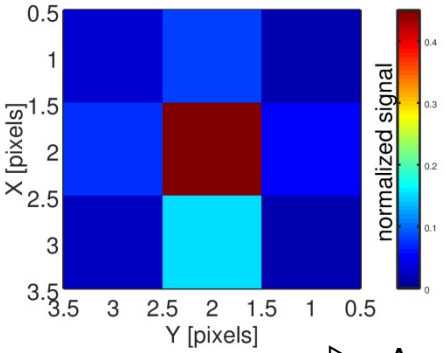
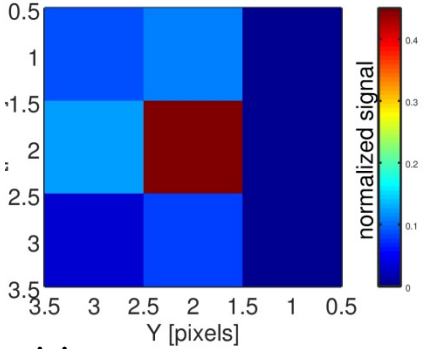
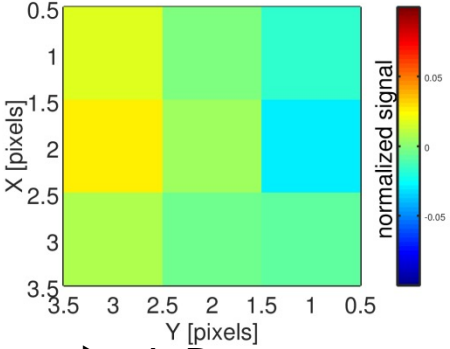
▷ measured



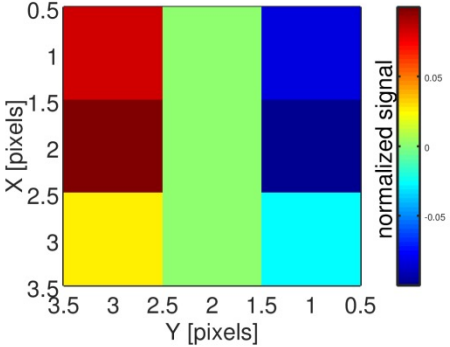
▷ simulated



▷ A sensitive

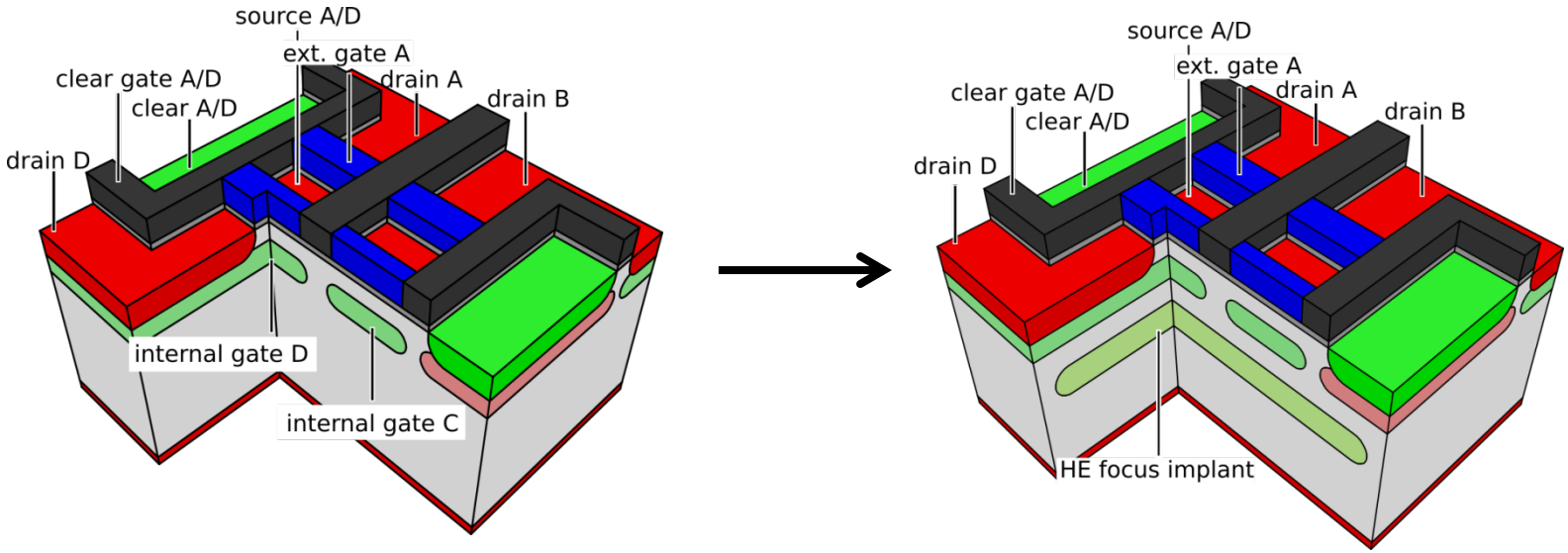


▷ A-D



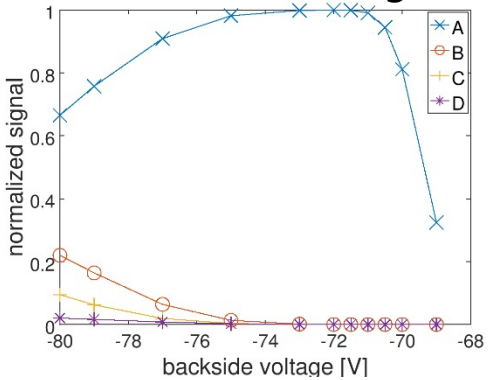
- ▷ qualitative agreement
- ▷ simulated spreading worse than measured
  - ↳ “illumination spot” not identical
  - ↳ different bulk thickness
  - ↳ simulation covers only a 3x3 array (edge effects possible)

- high energy implant aligned to the pixel structure

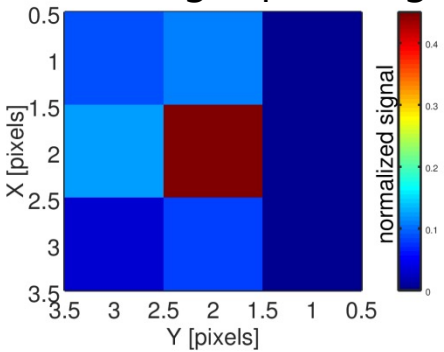


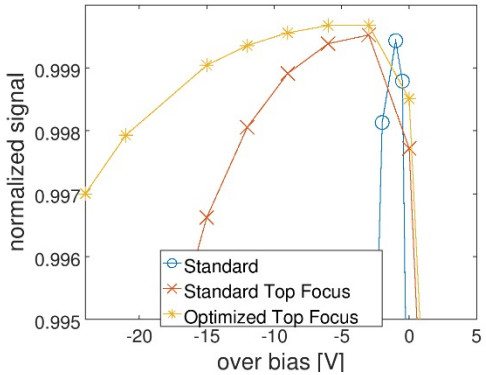
3D Simulation – Quadropix – improvements

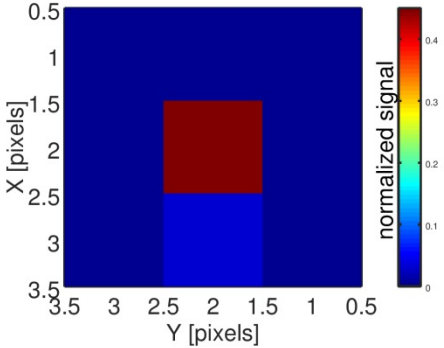
▷ backside voltage



▷ charge spreading







▷ standard
- ↳ functional
- ↳ selectivity > 1e4
- ↳ limited backside voltage
- ↳ large asymmetry of CC

▷ focussing he-implant
- ↳ improved operation window
- ↳ reduced charge spreading

Conclusion

- 2D simulations of DePFET
  - ↳ many basic properties can be simulated in 2 dimension
  - ↳ good agreement between simulation and measurements
  - ↳ simulations provide a tool to investigate device optimizations

- 3D simulations of Quadropix DePFETs
  - ↳ complex structures require 3D simulations
  - ↳ good agreement between simulation and measurements
  - ↳ simulations provide a tool to investigate device optimizations

Thanks for your attention