Detector Development at the MPG - HLL

Alexander Bähr on behalf of the MPG-HLL

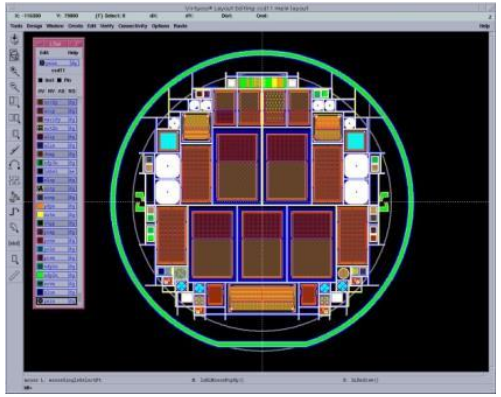
MPG HLL

New Building

- IPP Campus Garching - moved recently

sensor

- simulation
- design
- fabrication



- 1500 m² cleanroom area
- 600 m² ISO3 & ISO4 area
- 6/8 inch silicon process

Central facility of the Max Planck Society
~45 scientists, engineers and technicians
+ guest scientists, and students

camera

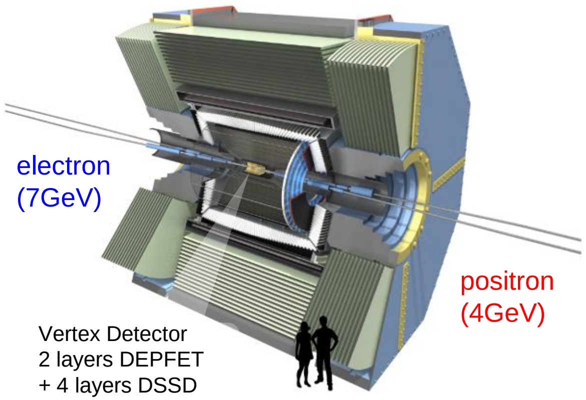
- design
- assembly
- test

(some) HLL Sensor examples

XMM-Newton

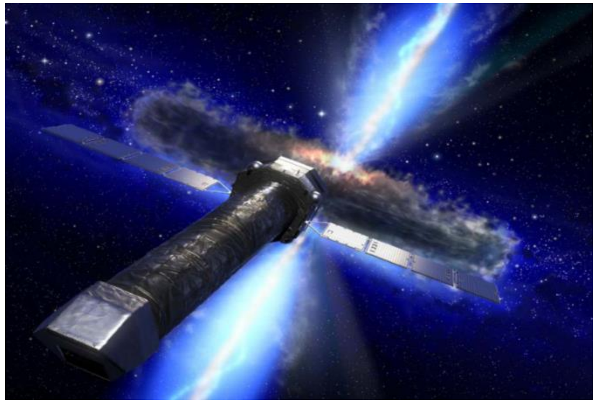
pnCCD
X-ray imaging spectroscopy
curtesy ESA

DePFETs at KEK - Japan



DePFET particle tracking

WFI aboard Athena



DePFET - X-ray imaging spectroscopy
curtesy ESA

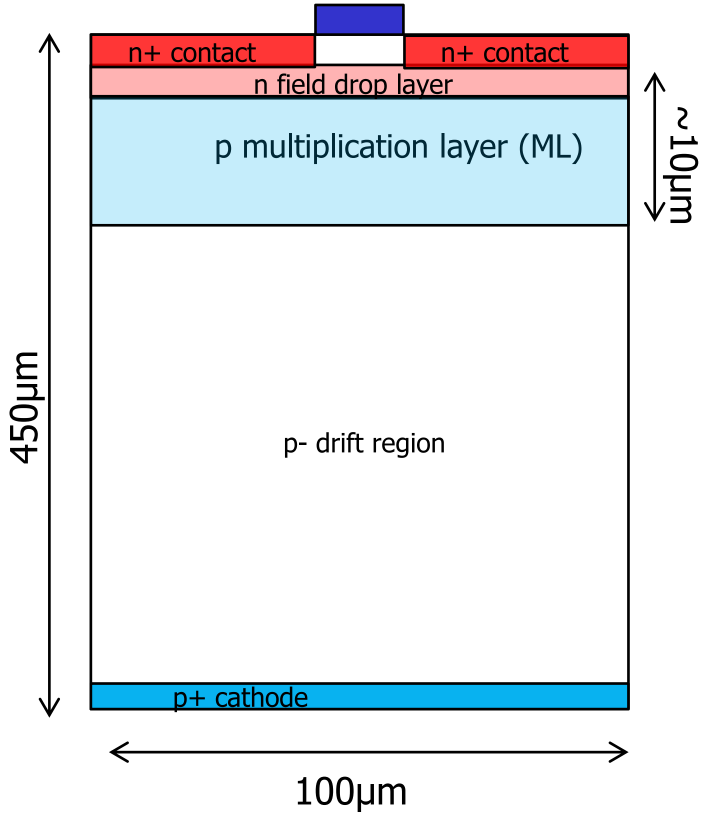
MIXS aboard BepiColombo

DePFET -planetary science
curtesy ESA

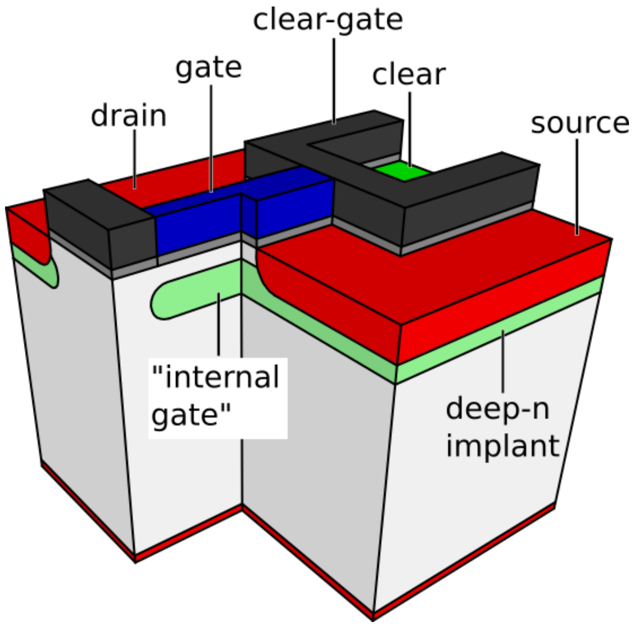
We also produce
-SDD (silicon drift detectors)
-Diodes
-Avalanche Diodes
-etc.

EXAMPLES FOR SIMULATIONS - AND CROSS CHECK WITH MEASUREMENTS

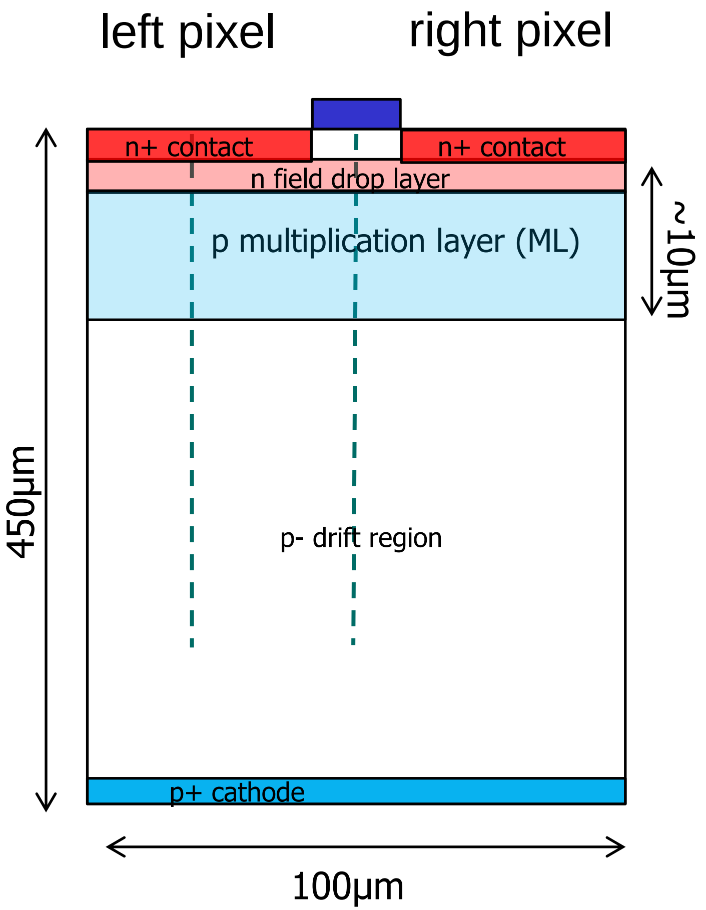
MARTHA (LGAD)

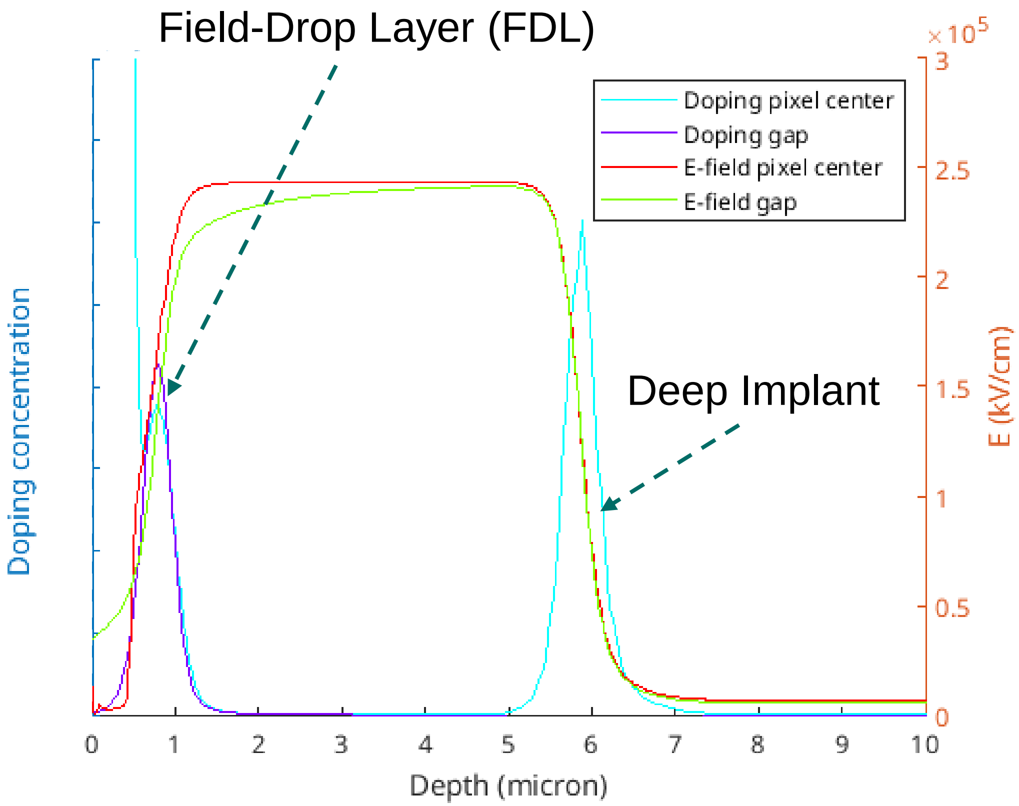


DEPFET (Active Pixel Sensor)



2D SIMULATION - ELECTRIC FIELD





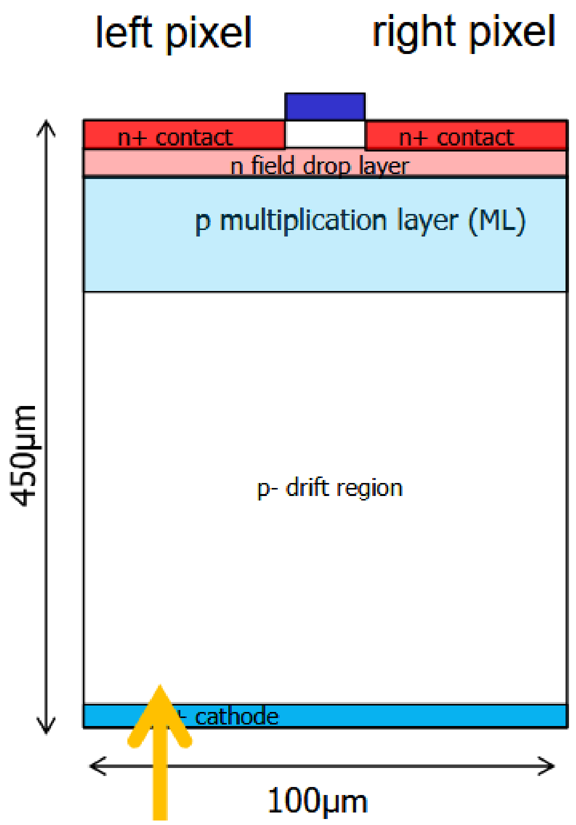
deep Implant

- **extended ML**
- **lower field**
- **low k-factor**
- **low excess noise**

FDL:

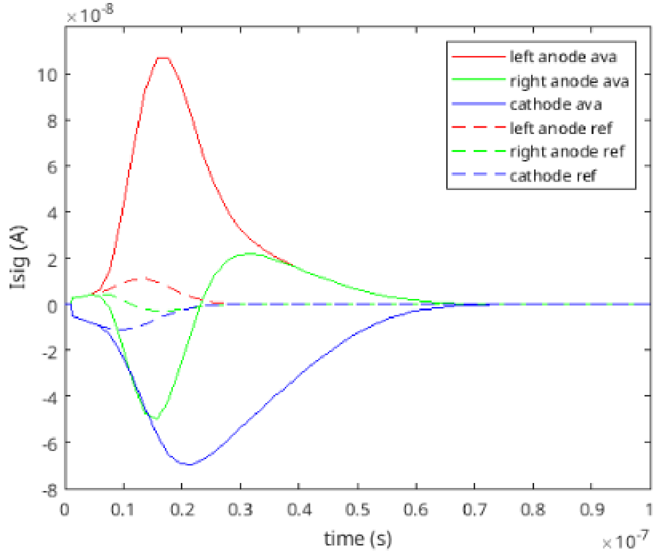
- **shift Max E-Field**
- **prevent breakdown**

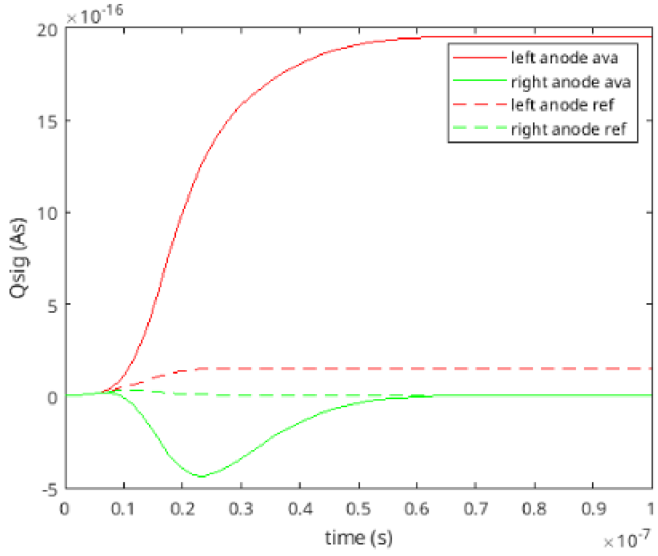
SIMULATED SIGNAL EVOLUTION



generate test charge
Qtest = 1.3×10^{-16} C

solid - with avalanche
dashed - without avalanche (pin diode)



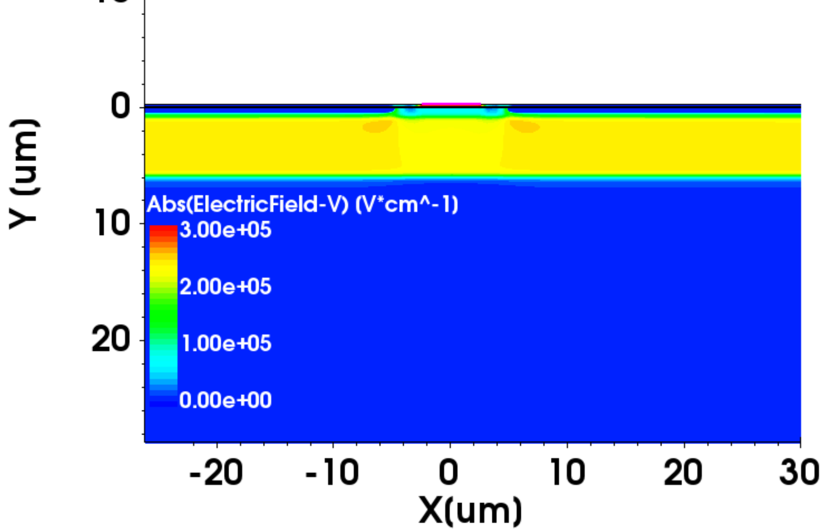


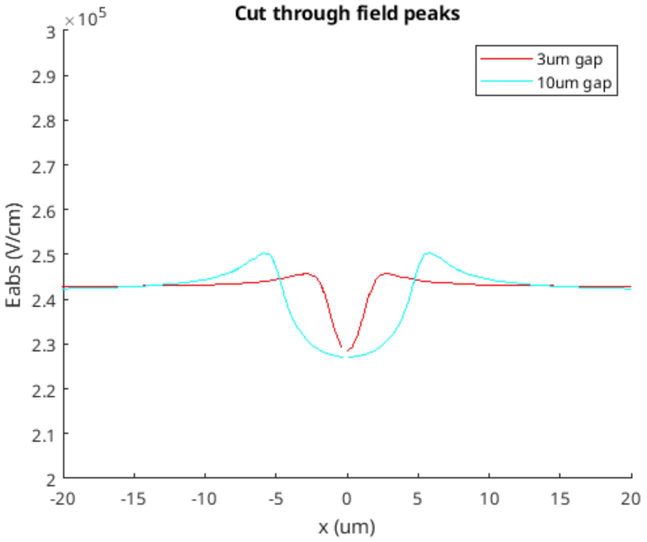
full signal formed faster in pin diode
(generated holes have to drift to backside)
'anti cross talk'

-> M = 14.8

2D SIMULATION - ELECTRIC FIELD

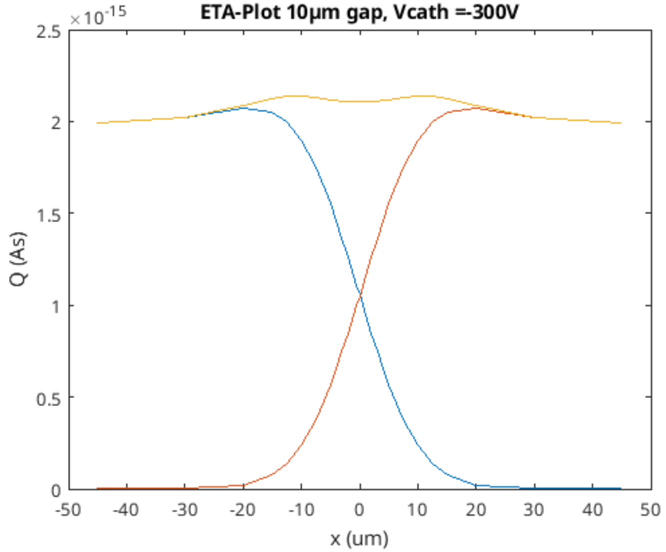
HF region and field drop layer extend over pixel gaps

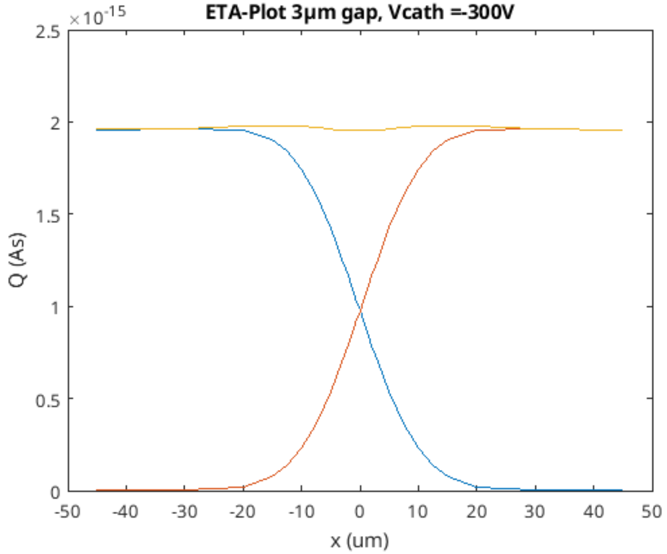




Electric field

„overshot“ at gap corners





amplified signal

gain also in gap region

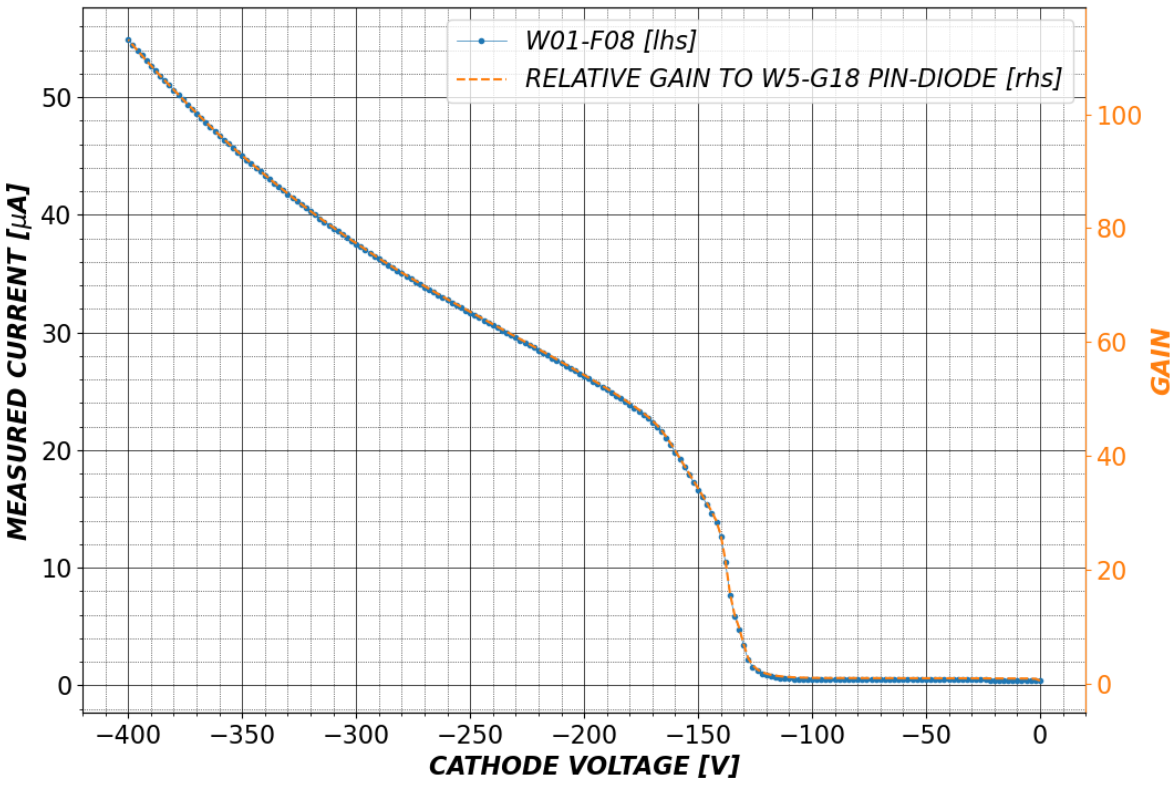
field „overshot“ leads to gain variation

overshot depends on gap size

(and operation conditions)

GAIN OF FIRST PROTOTYPE(S)

high gain diode



gain measurement

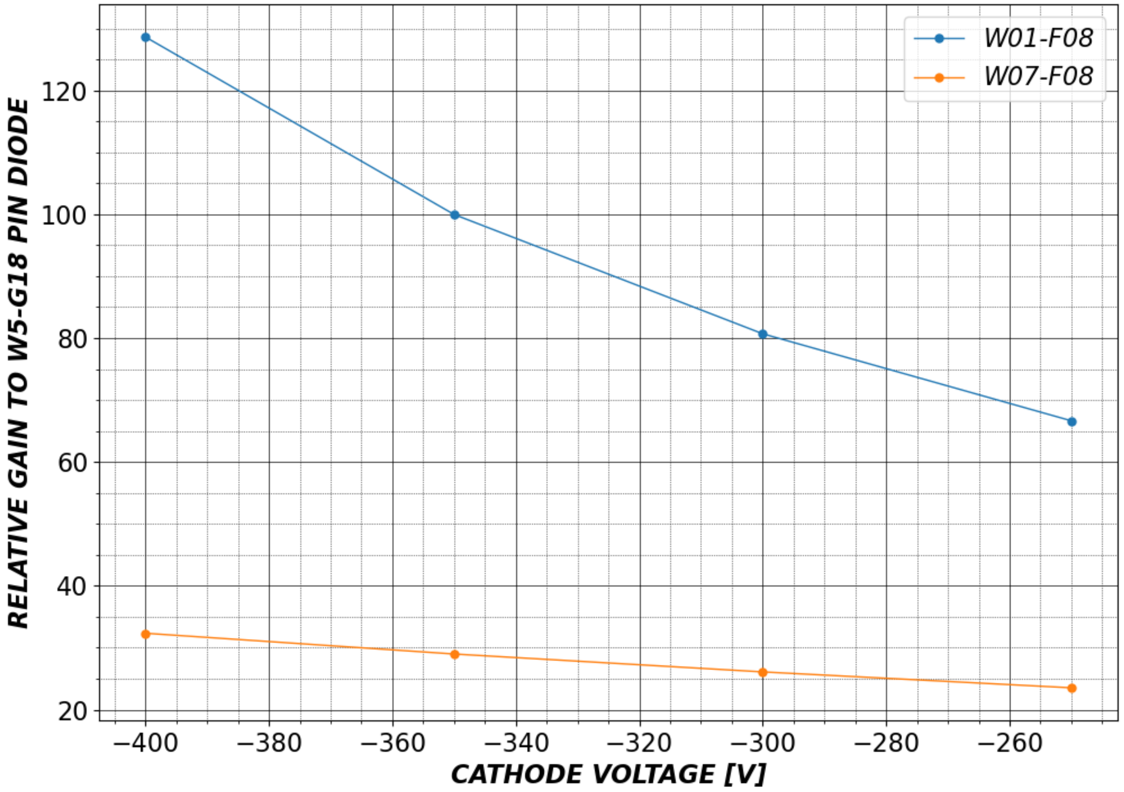
- **diode illuminated by laser**
- **measure photocurrent of APD and PIN diode**
- **Gain as ratio of photocurrents**
- **backside voltage sweep**

steep current increase at -140V

- **depletion of MR**
- **further increase of gain with backside voltage**
- **gain of ~80 @ -300 V**

PRODUCED GAIN RANGE

high gain and low gain diode



comparision of gain of two APDs from different wafers

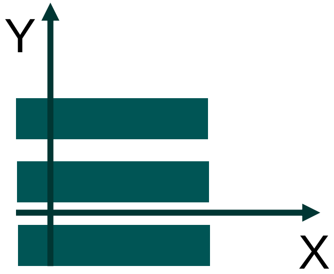
full depletion @ -250V

- **depletion of MR + Bulk**

high gain of 81 @-300V

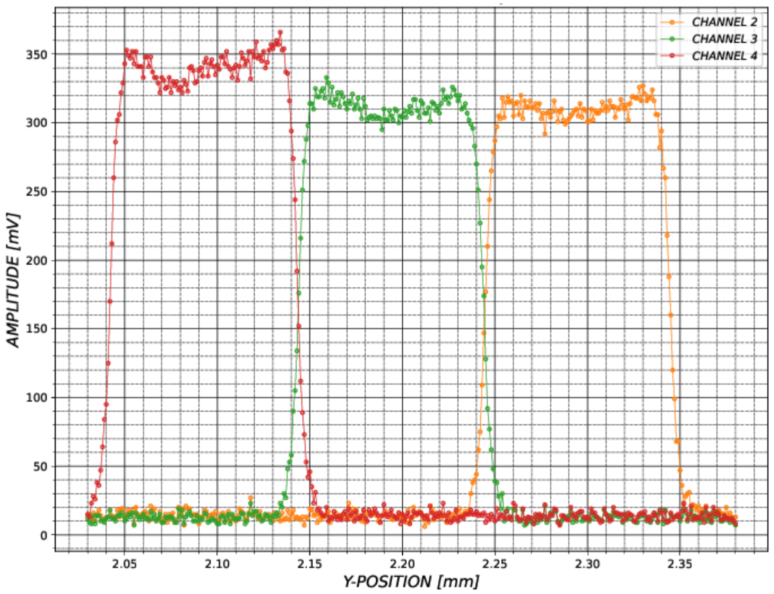
low gain of 26 @-300V

GAP BEHAVIOUR OF FIRST PROTOTYPE

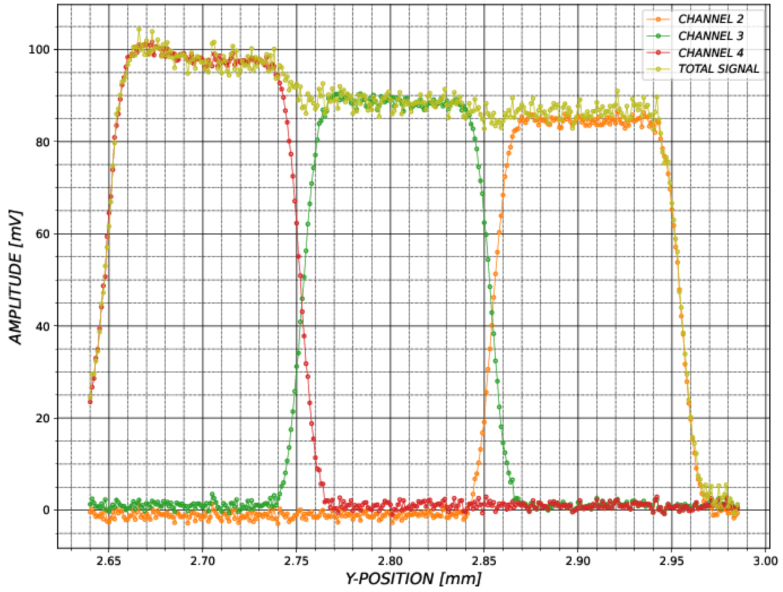


strips
3 µm gap

high gain strips



low gain strips



40 ns Laser Puls ~ 11000 e$^-$

laser focussed to ~ 10 µm

different signal height due to variation of the ROE (parasitic capacity on PCB)

„overshot" related to field in gap region

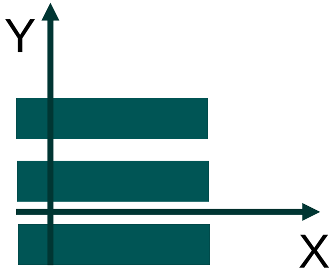
optimized settings: gain in gap-region (mostly) constant

gap isolation functional

overshot for high gain (as expected)

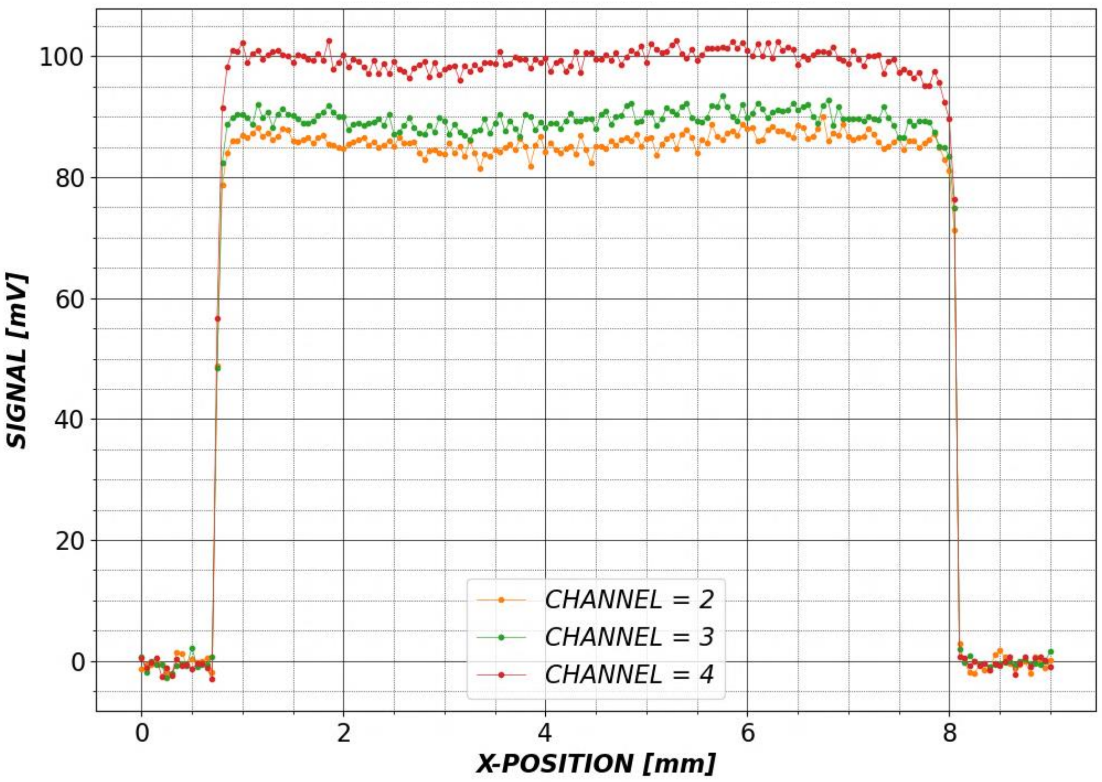
no inter pixel dead space

GAIN HOMOGENEITY



strips
3 µm gap

low gain strip



laserscan over the length of the strip.

no significant change of signal over 7 mm

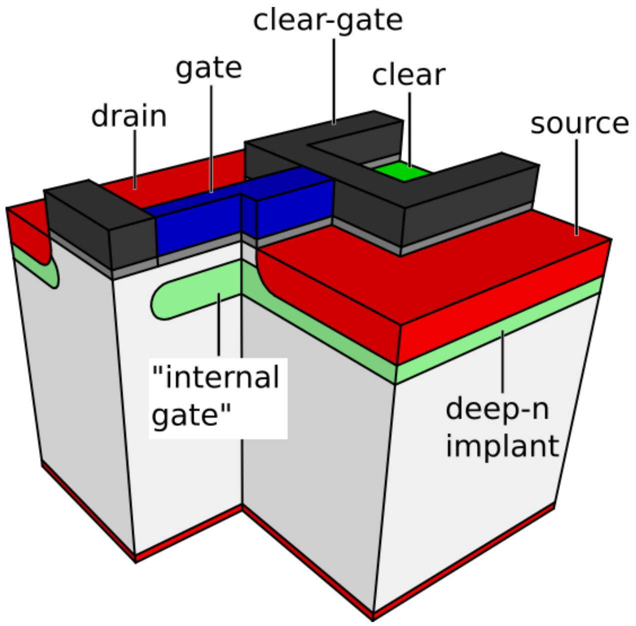
good homogeneity over small scales

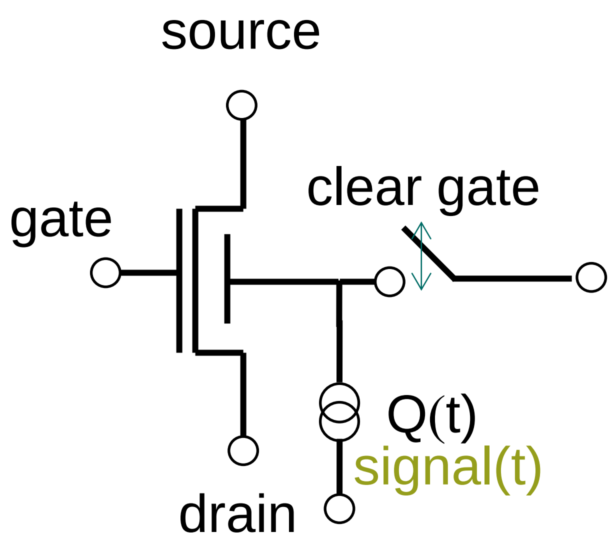
MARTHA

Simulations are great for

- **device understanding**
- **first test of new ideas**
- **investigate limitations of sensors**
- **faster than sensor production**

EXAMPLES FOR SIMULATIONS - THE DEPFET





- MOSFET on n-substrate
- deep-n implant below gate
  - positive potential
  - „internal gate“ (IG)
  - conductivity modulated by electrons
- reset via clear and clear gate
- good signal to noise
- unobstructed backside contact
- typical charge gain values ~420 pA/e$^-$

Applications:
- Belle II, BepiColombo, Athena, EDET, etc.

2D SIMULATION FLOW

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

Signal Response

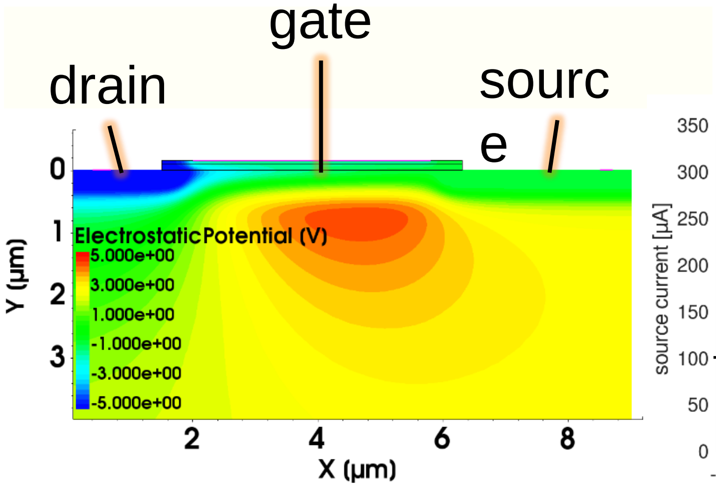
charge gain (current readout)
gain (source follower)

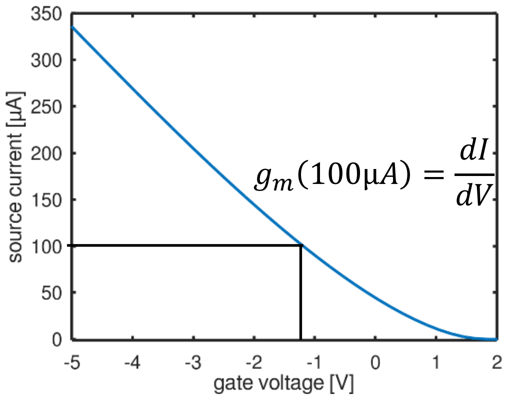
Noise

at the moment only white noise
1/f noise not sufficeintly qualified

Impact Ionization

cause additional electrons in the internal gate





COMPARING MEASUREMENTS AND SIMULATIONS – 2D GAIN AND TRANSCONDUCTANCE

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

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 →

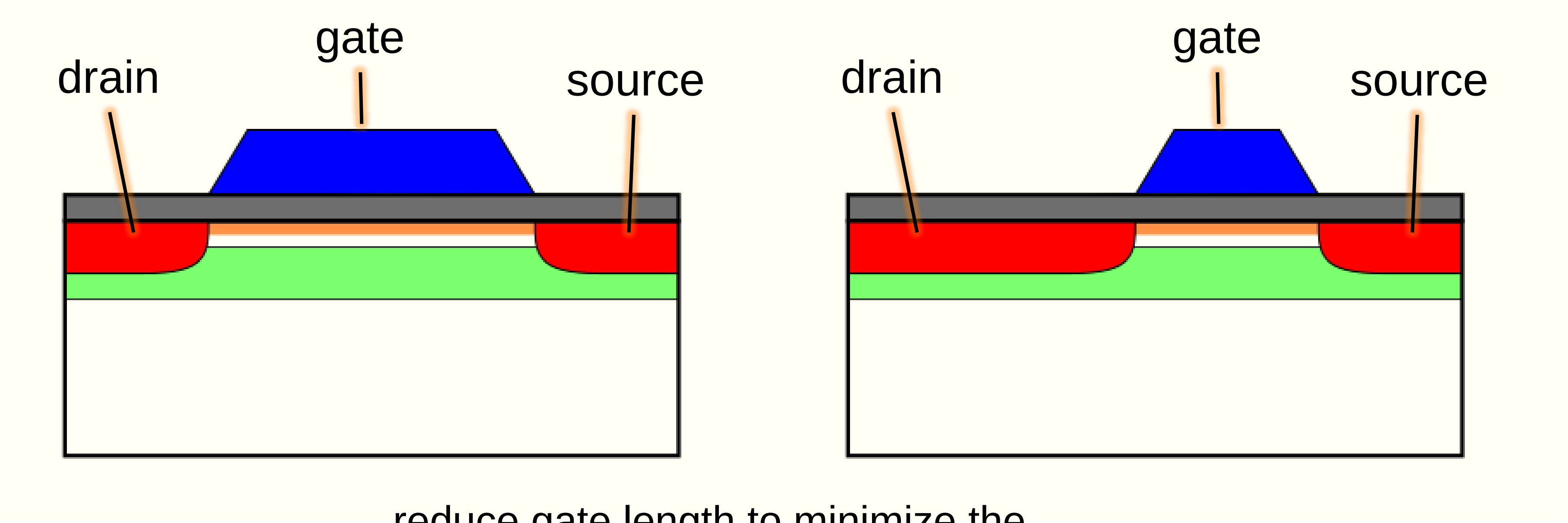
VERIFICATION OF SIMULATIONS

- 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

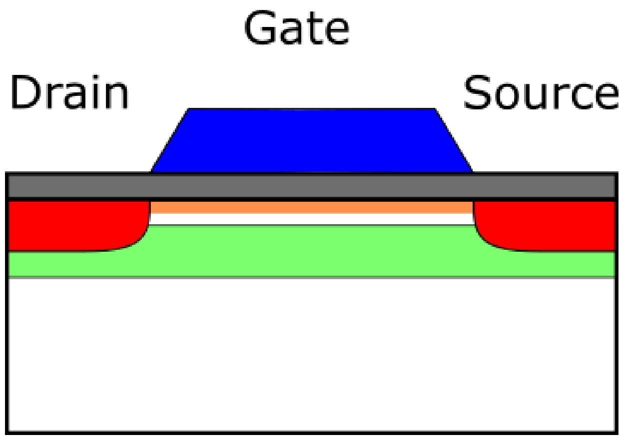
- utilize simulations for study of DePFET improvements

IMPROVING THE DEPFET - SCALING

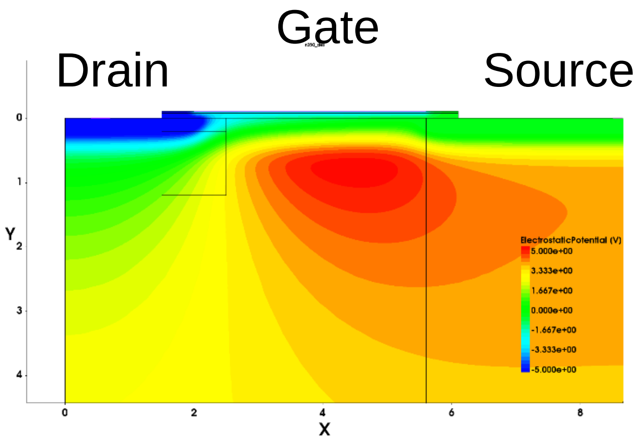


reduce gate length to minimize the
internal gate and increase charge gain

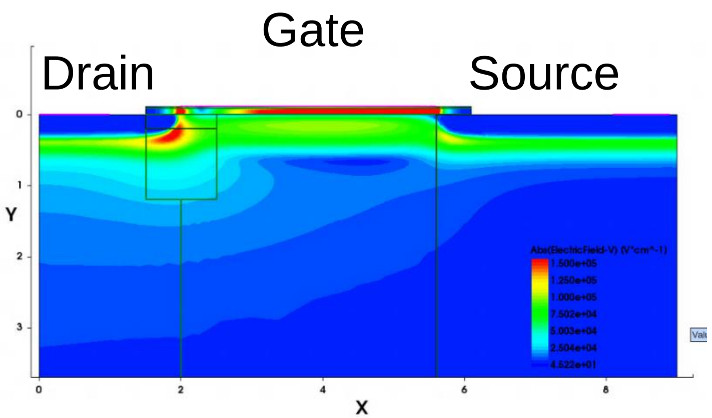
COMPARING MEASUREMENTS AND SIMULATIONS – 2D IMPACT IONIZATION



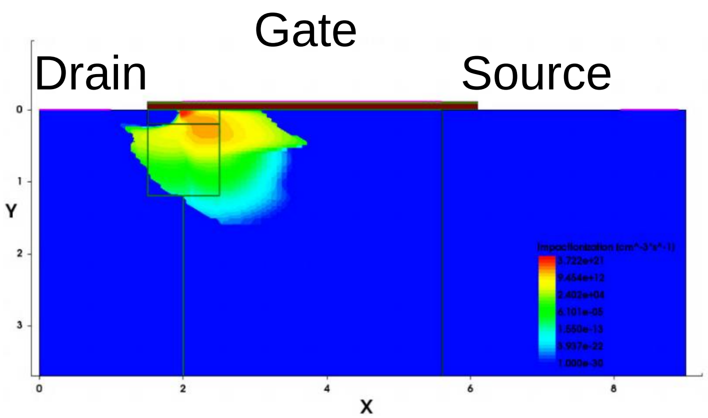
Potential Distribution



Electric Field

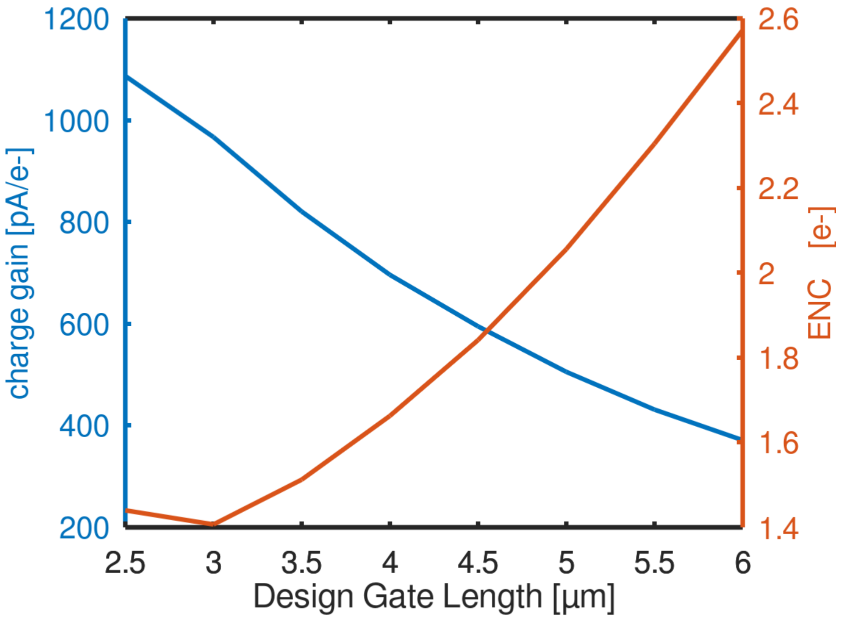


Impact Ionization

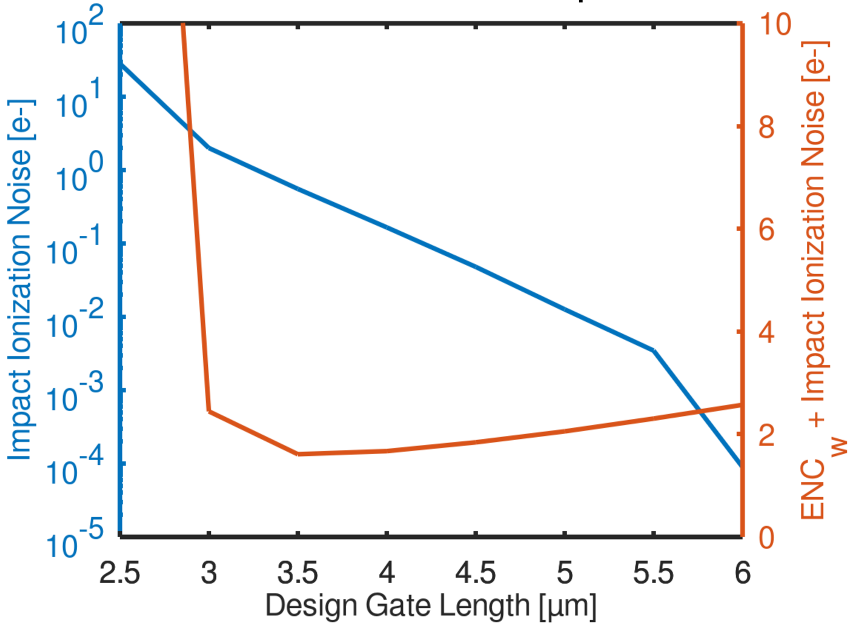


IMPROVING THE DEPFET - SCALING

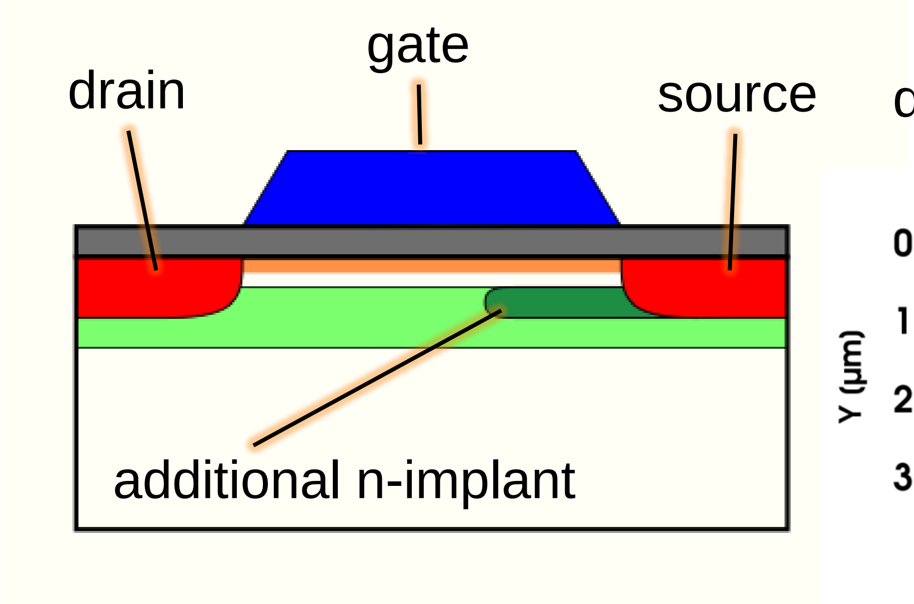
gate width of 20µm
readout time of 5 µs

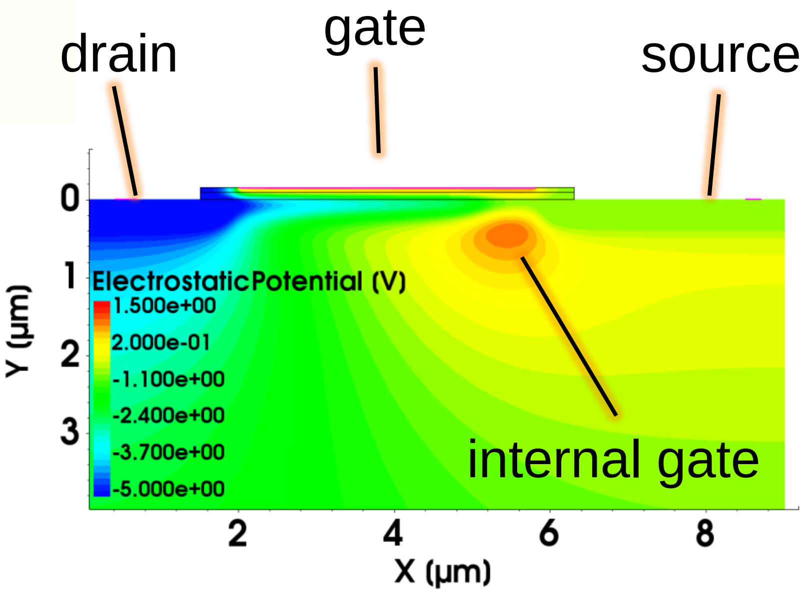


gate width of 20µm
readout time of 5 µs

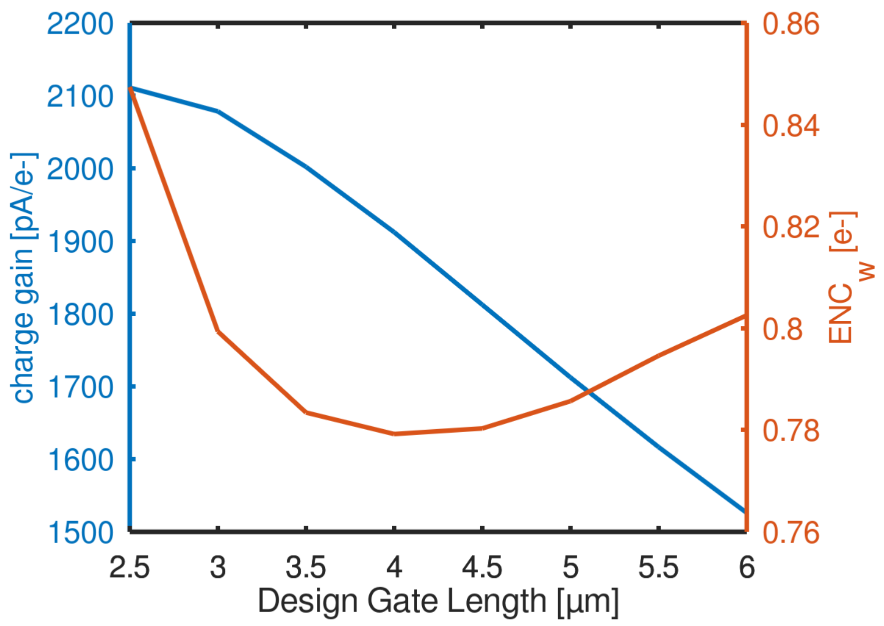


IMPROVING THE DEPFET - SUPER G_Q

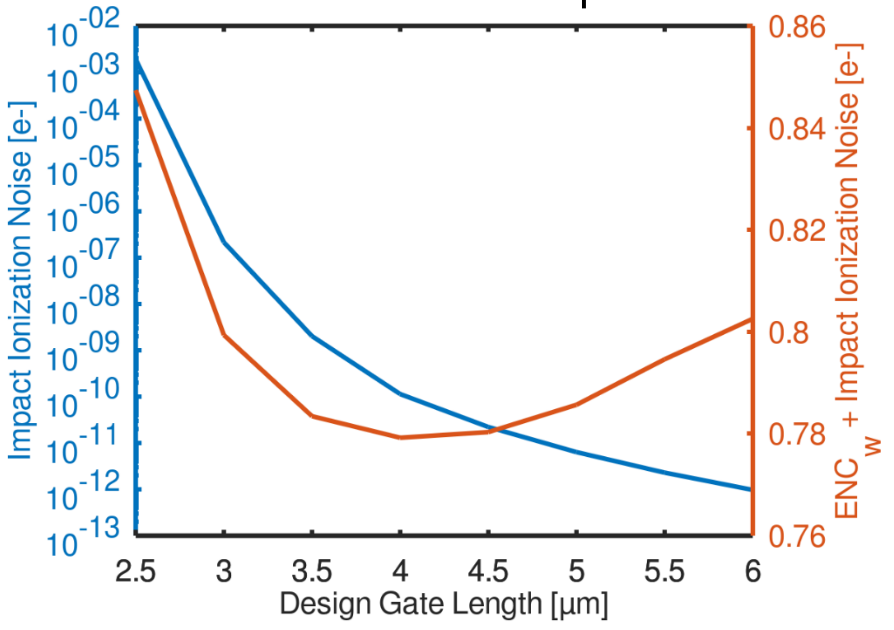




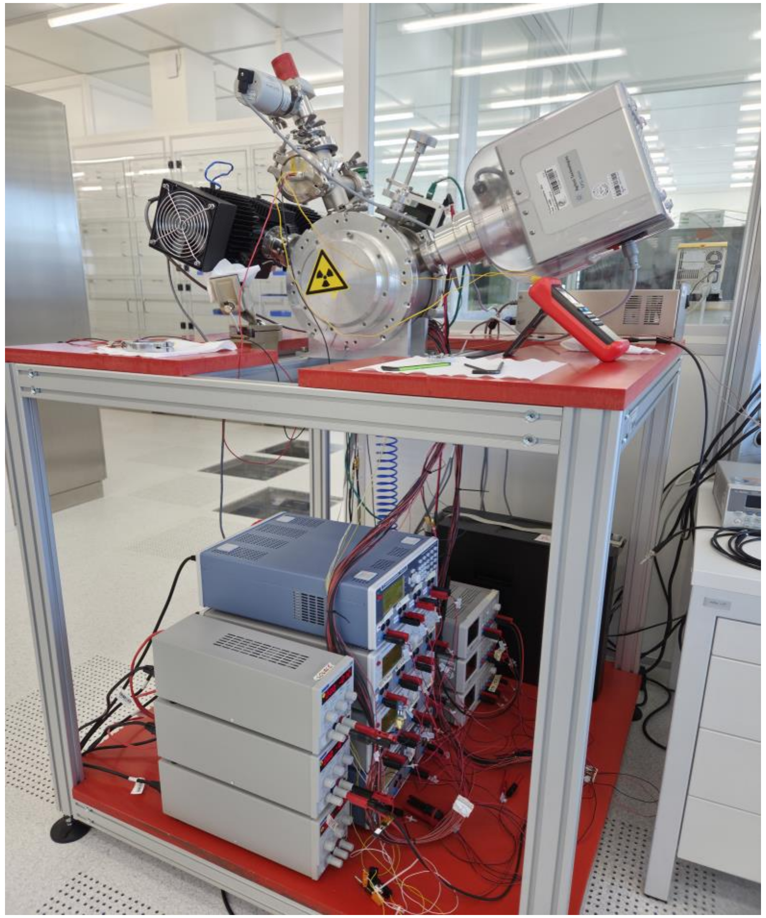
IMPROVING THE DEPFET - SUPER G_Q



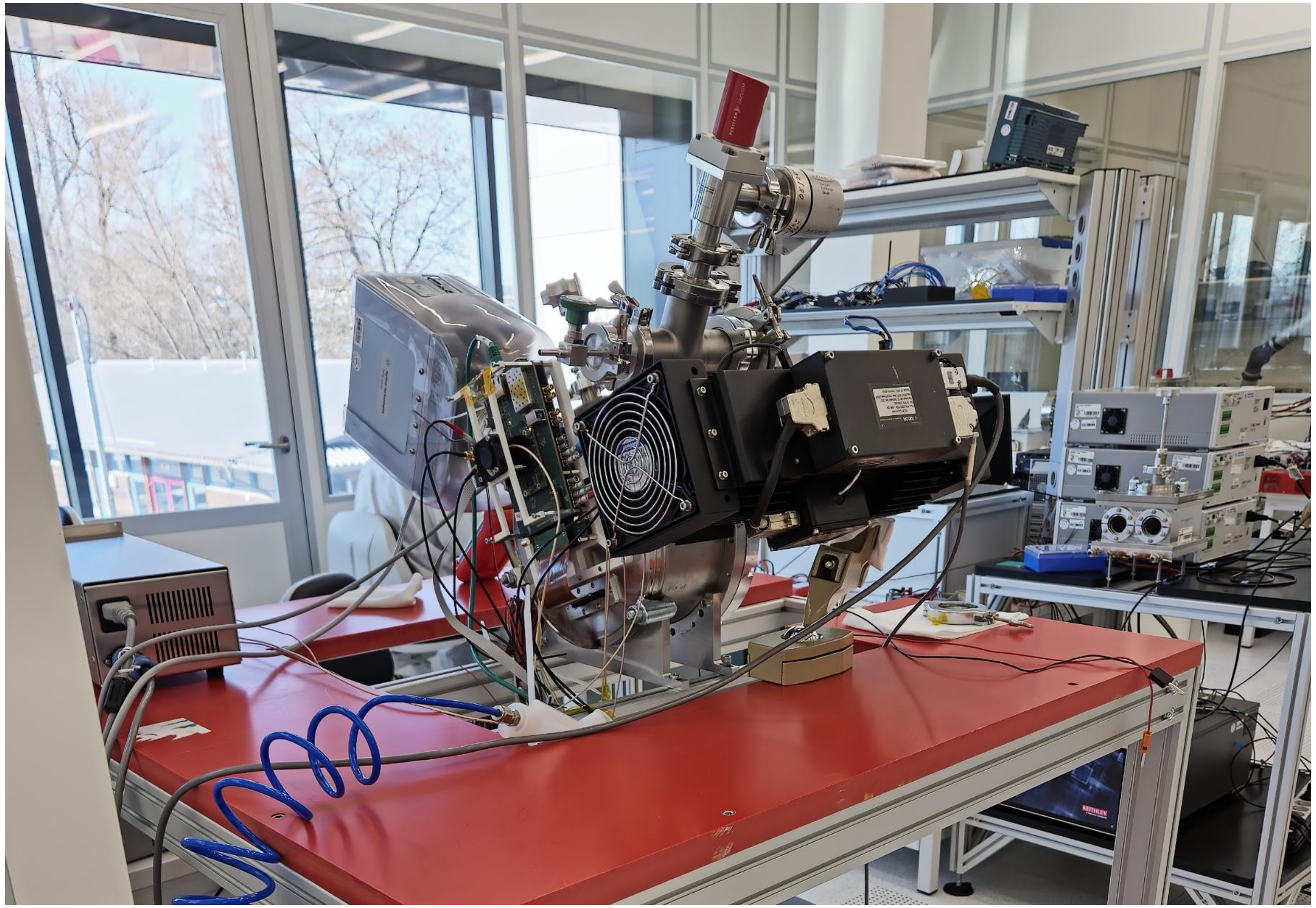
gate width of 20µm
readout time of 5 µs



EXPERIMENTAL SETUP
Instrumentation



Power supplies beneath the table, Vacuum pump top right, Cryo-Cooler top left.

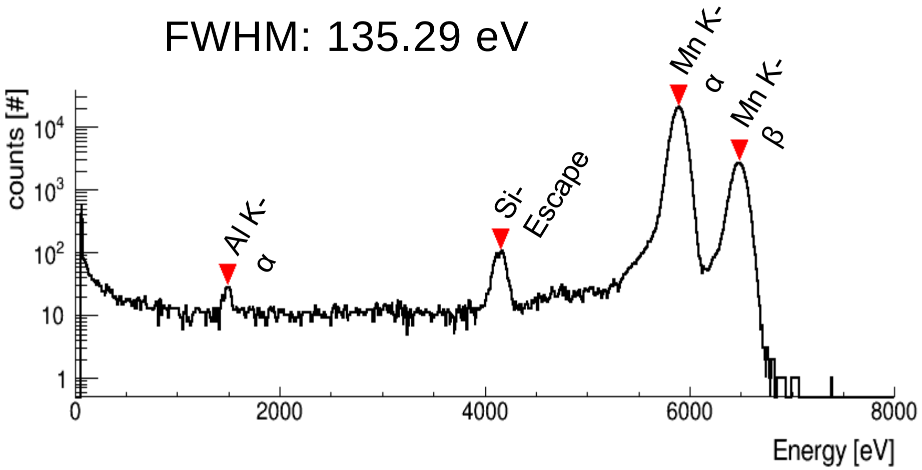


Center: PCB-Stack of XU1, MSM, MSMA and flex cable.

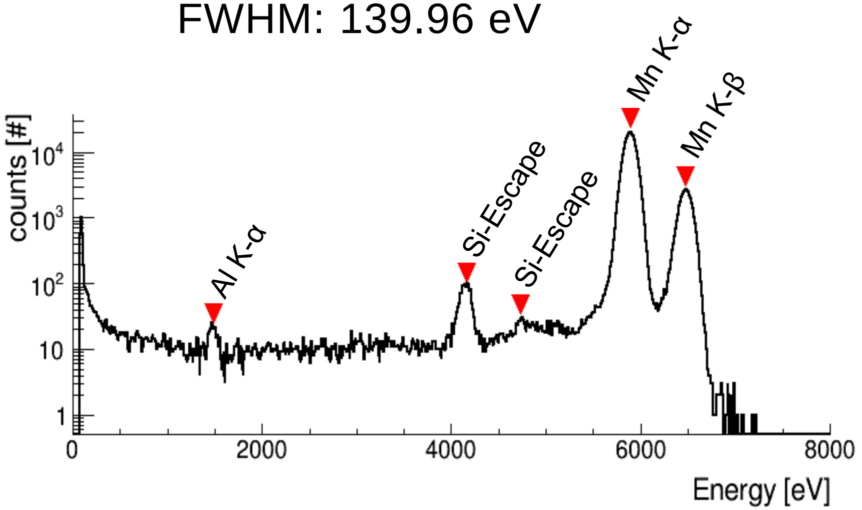
COMPARISON TO STANDARD TECHNOLOGY

test devices 64x64 DePFET matrix

Standard
Mean: 5893 eV
Mean: 5050 ADU
FWHM: 135.29 eV



Super g_q
Mean: 5893 eV
Mean: 13077 ADU
FWHM: 139.96 eV

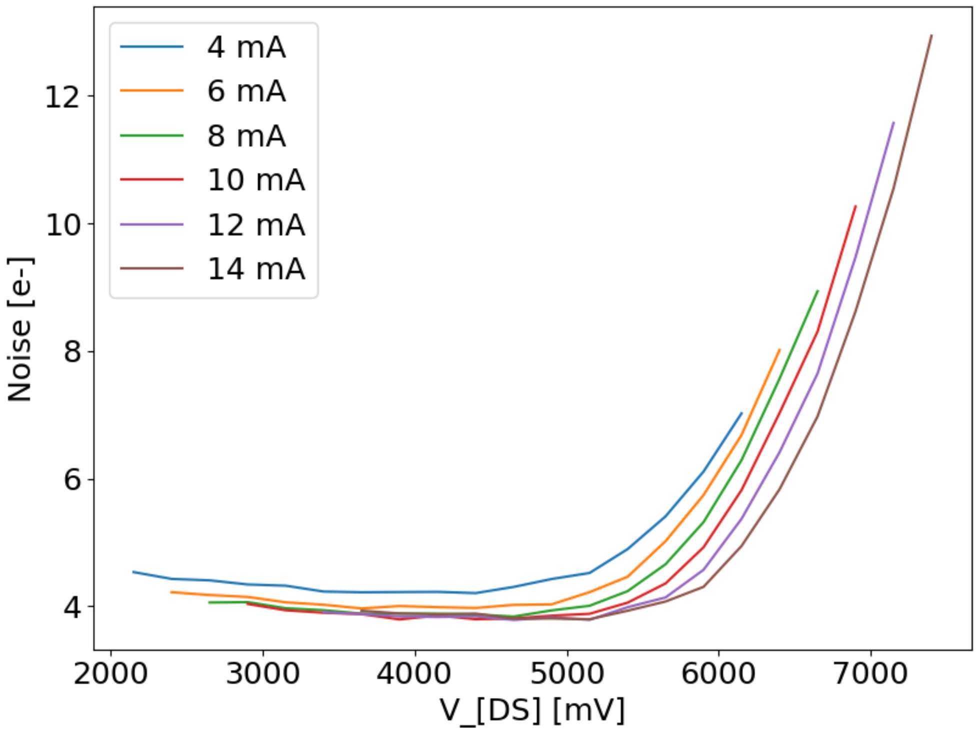


	Standard @ 100µA/pix	**Super-g_q @ 100µA/pix**	***Super-g_q good Noise***	***Super-g_q good Gain***
Charge Gain [nA/e^-]	0.769	1.77 (x 2.3)	*1.74 (x 2.26)*	***2.13*** *(x 2.77)*
Noise Mean [e^- ENC]	**3.5**	10.72	*4.6*	*6.3*
Energy Res. (all events) [eV]	135	189	*140*	*166*

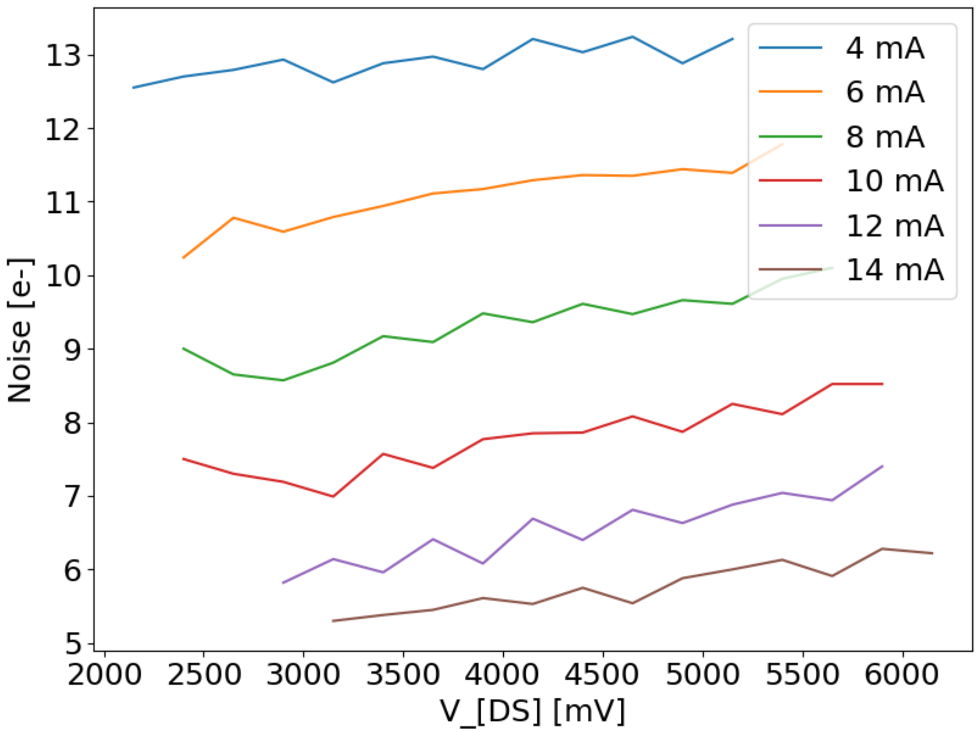
preliminary

NOISE VS CURRENT

Standard DePFET



Super g_q DePFET



preliminary

DEPFET SUPER-GQ SIMULATIONS AND MEASUREMENT

Good news: more than 2x higher gain achievable with super-gq DePFET

Bad news: When you leave known territory

you may encounter effects not covered by simulations

thorrogh investigation required to understand observed issues

Further investigation is ongoing

MAX PLANCK SEMICONDUCTOR LABORATORY

THANKS FOR YOUR ATTENTION

Alexander Bähr on behalf of the MPG-HLL