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Tuneable linearity in HfO_2 based multilevel FeFETs for neuromorphic computing

M. Lederer, T. Kämpfe, T. Ali, K. Seidel

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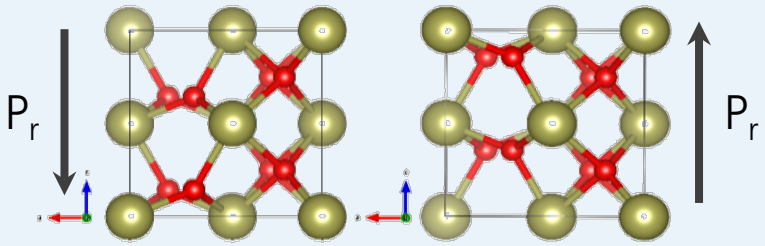
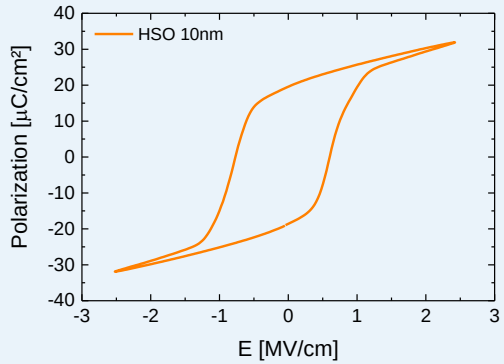
Ferroelectric Fieldeffect Transistor (FeFET)

Ferroelectricity in HfO_2

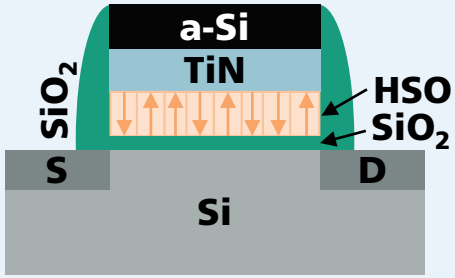
Orthorhombic ($Pca2_1$)

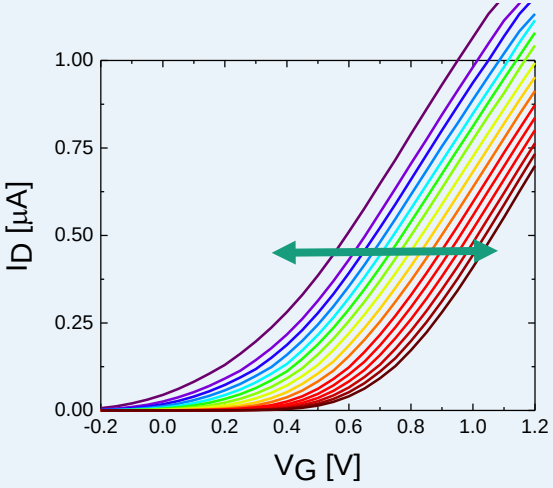


- Stabilized by Dopants, Stress, …

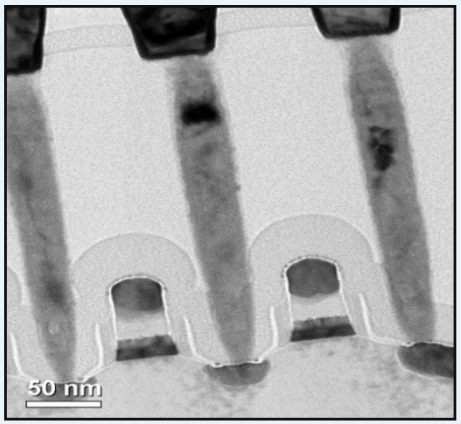


FeFET Gate Stack





28nm Proof of Concept



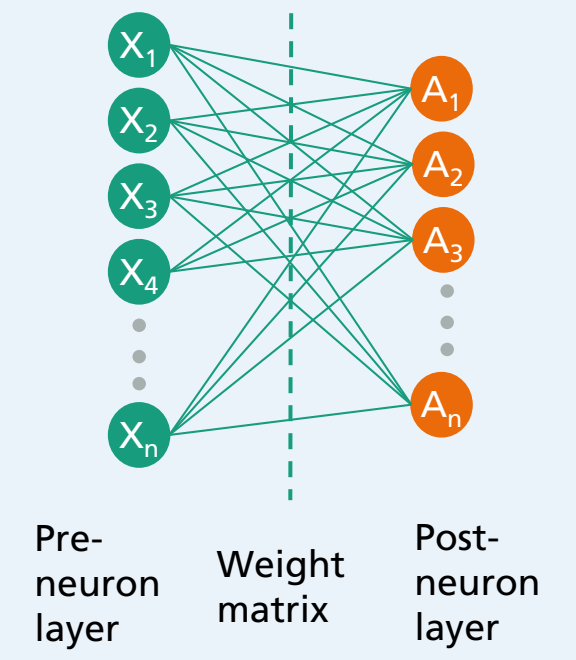
- Gate-First
- ΔV_T = 1-1.2 V
- ±5V, < 100 ns
- 10^4 endurance
- 10y retention

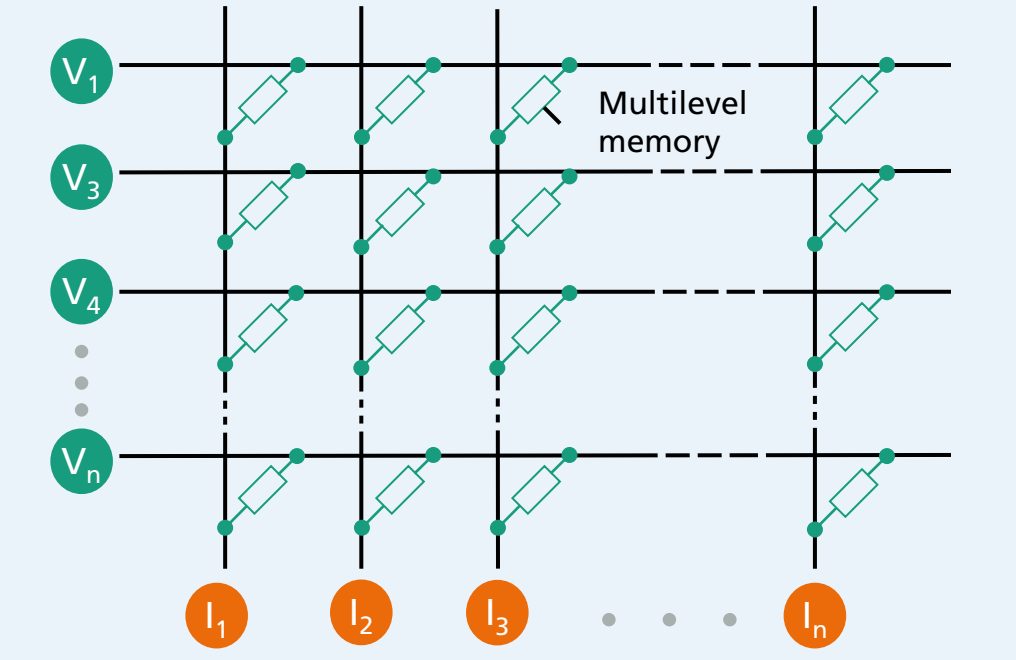
J. Müller et al., VLSI (2012)

Neuromorphic Computing

Dot-product engine

- Conductance of crossbar array represent weight matrix
- Level-based representation
- Most efficient for fully connected layers

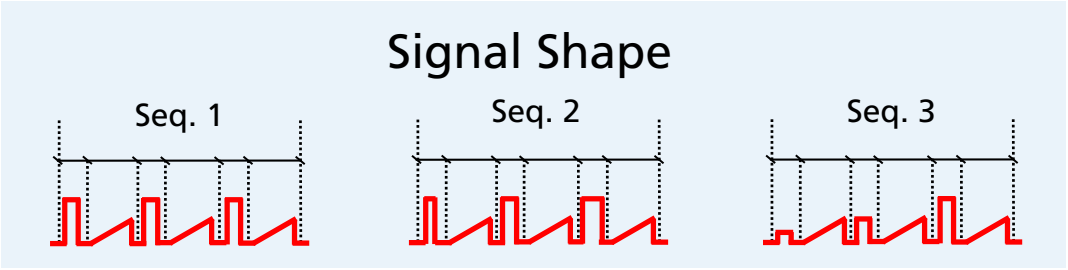




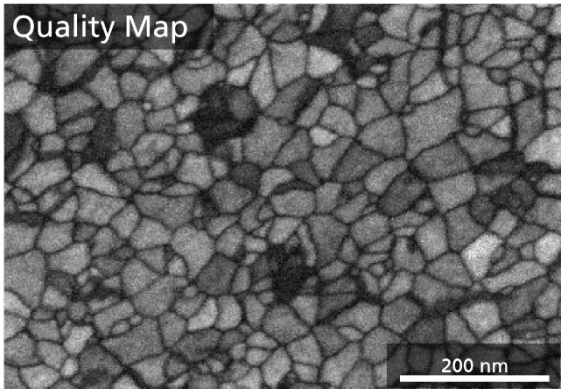
Fraunhofer IPMS

Non-Linearity Coefficient

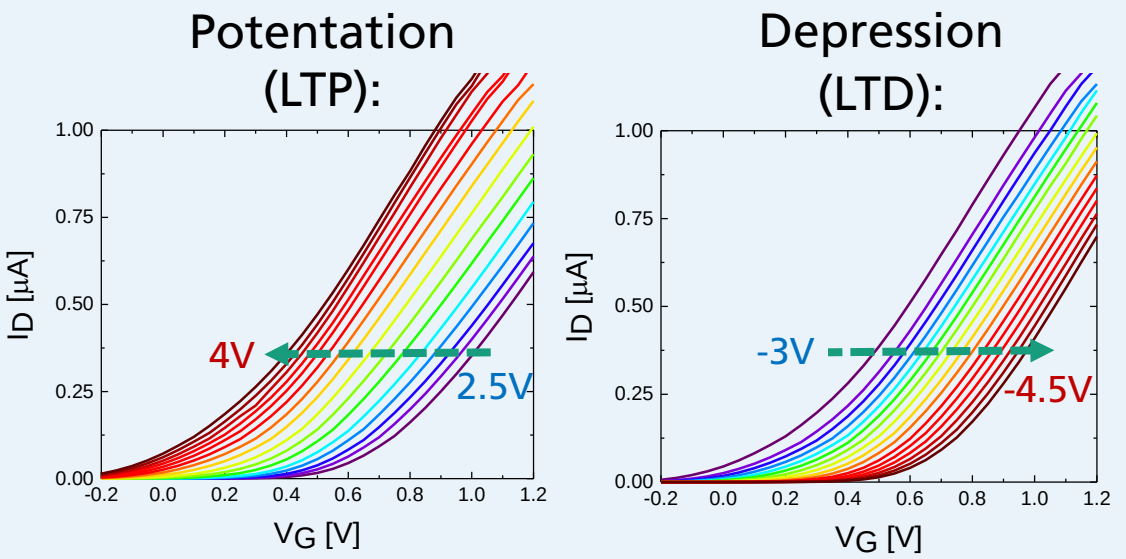
- Switching polarization of grains/domains
  - Shifting the threshold voltage



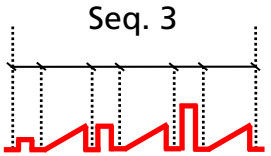
Transmission EBSD:



Seq. 3: 150ns W: 50 µm, L: 25 µm



Non-Linearity Coefficient



1. Nonlinearity Fit:

$$I_{p,d} = B\left(1 - \exp\left(\frac{P - D}{A}\right)\right) + C$$

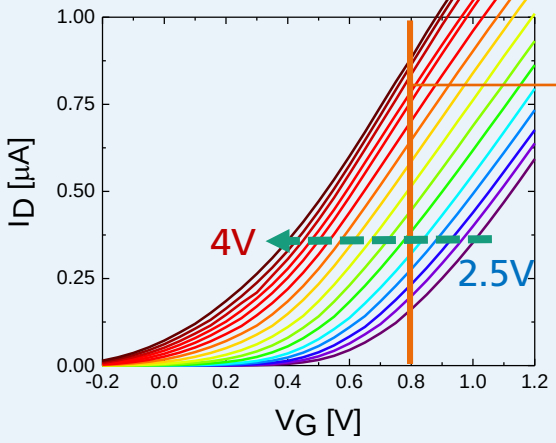
P := Pulse Number
D := Start Pulse Number

2. Nonlin. Coefficient:

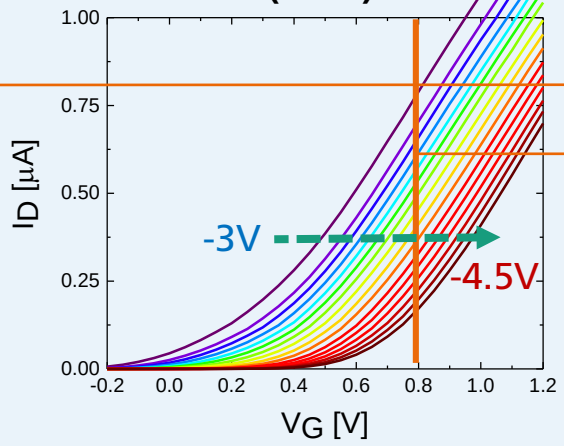
$$\alpha_{p,d} = \frac{1.726}{A + 0.162}$$

M. Jerry et al., IEDM (2017)

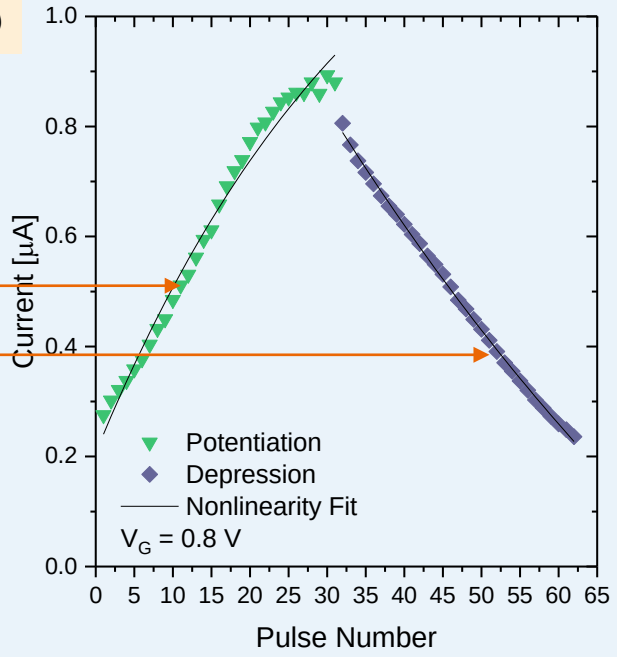
Potentation (LTP):



Depression (LTD):



Seq. 3: 150ns W: 50 µm, L: 25 µm

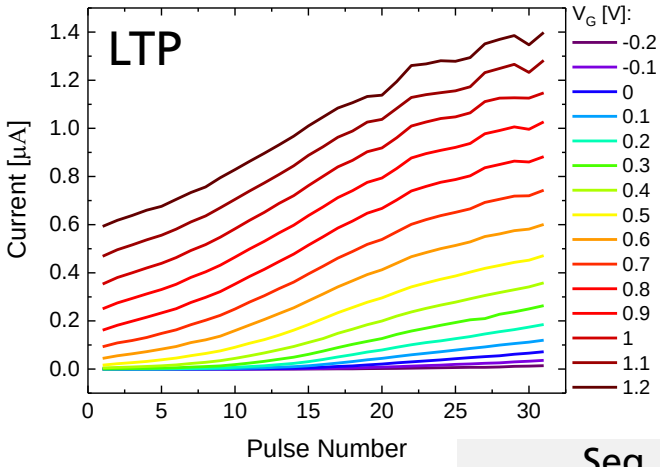


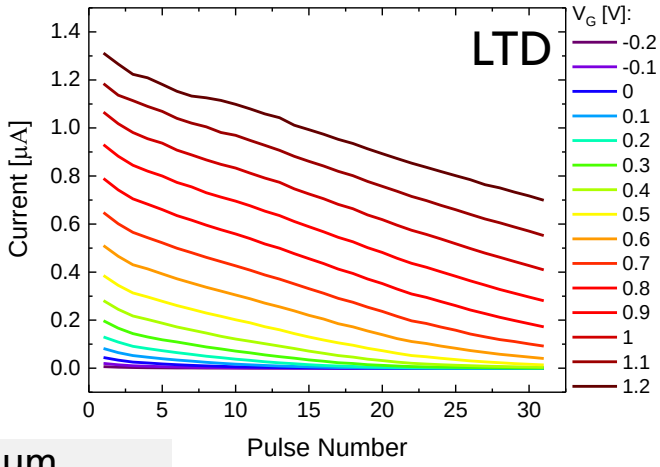
Non-Linearity Coefficient

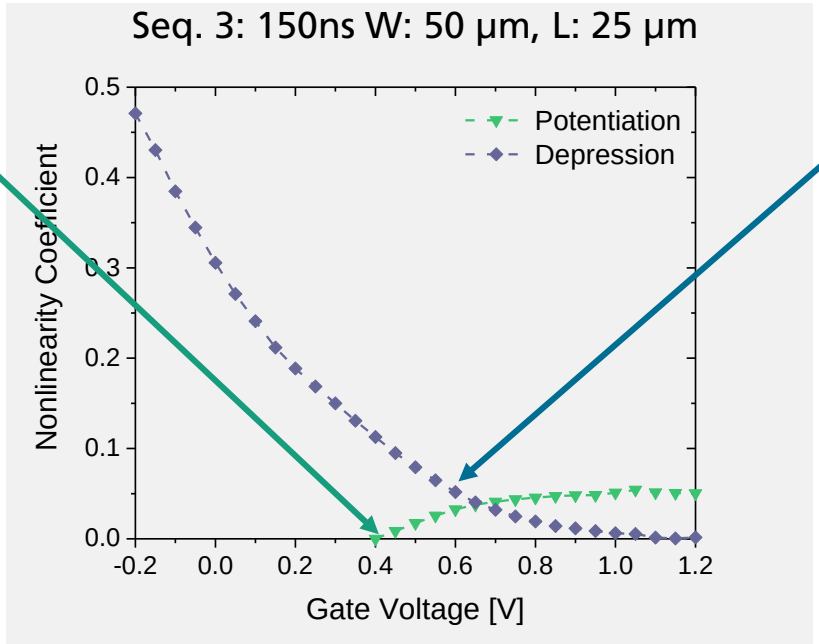
- Comparison of different non-linearities

  0.21
  0.12
  0.00 (1.02*10^-7)

Influence of the Gate Voltage

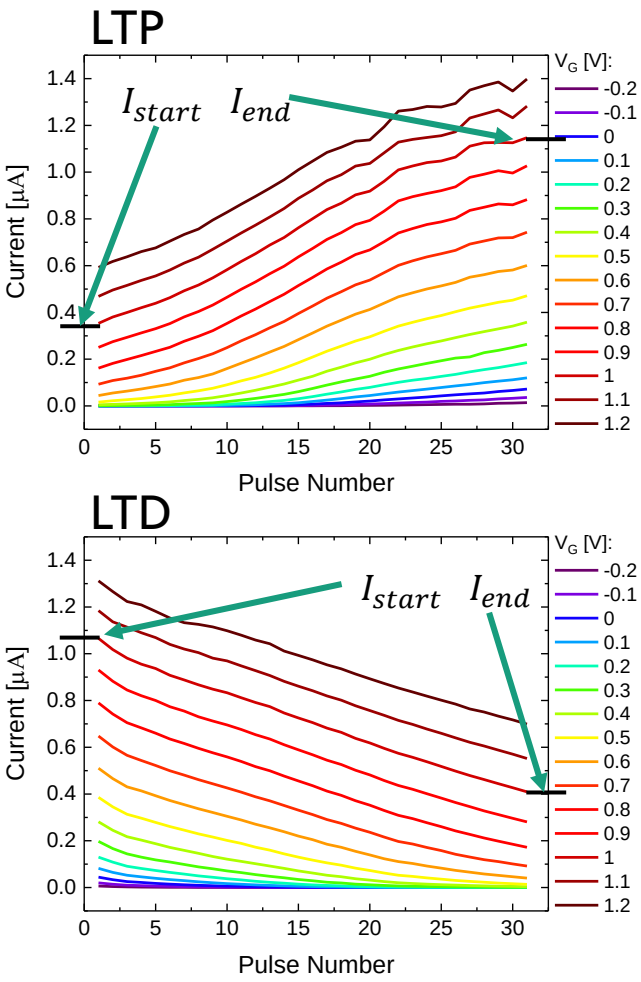


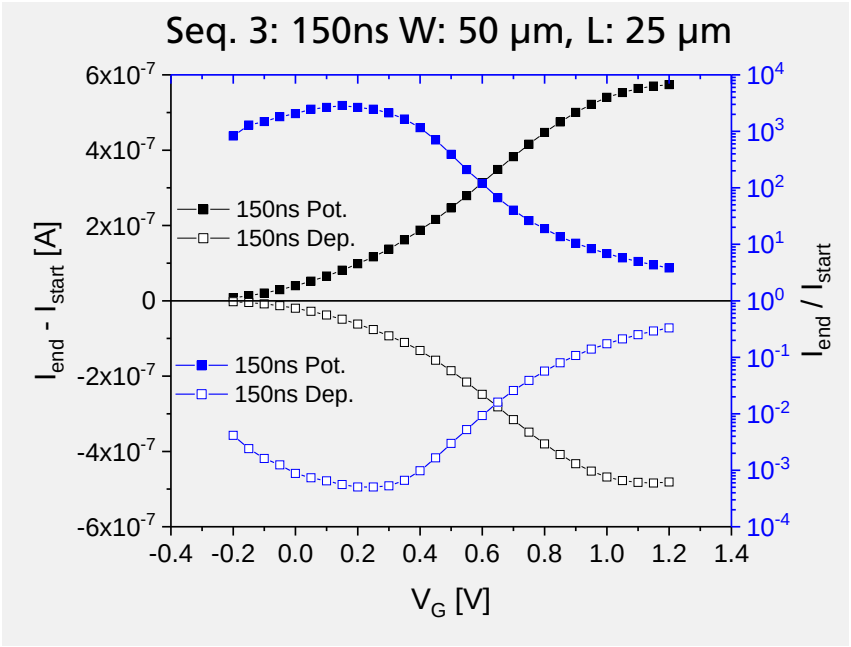




- Nonlinearity is strongly dependent on gate voltage

Influence of the Gate Voltage

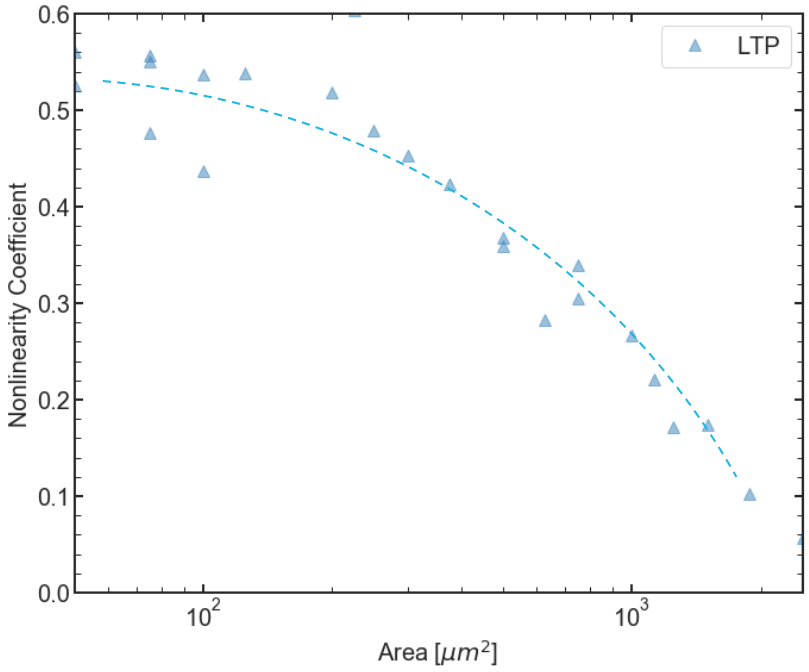


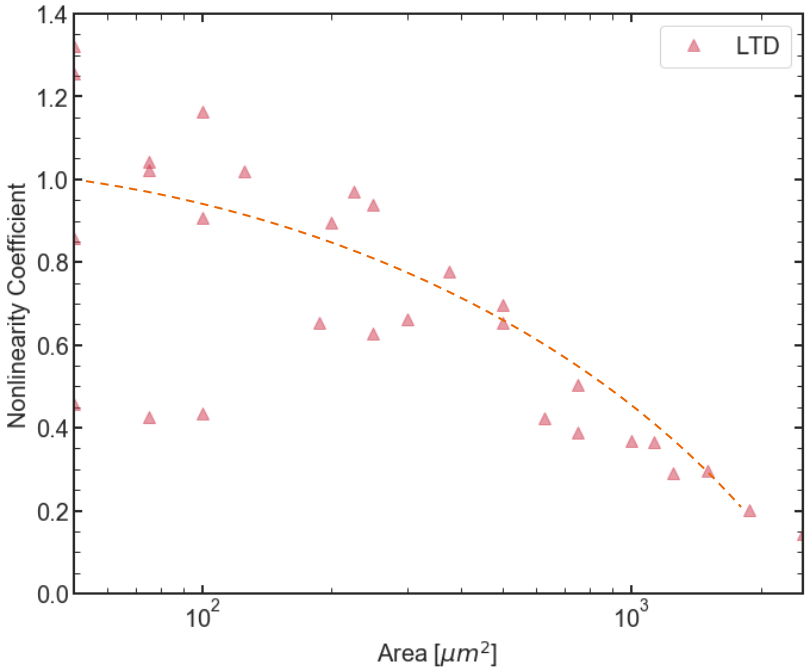


- Dynamic range strongly dependent on gate voltage
- Relative and absolute range show maximum at different gate voltages

Area scaling

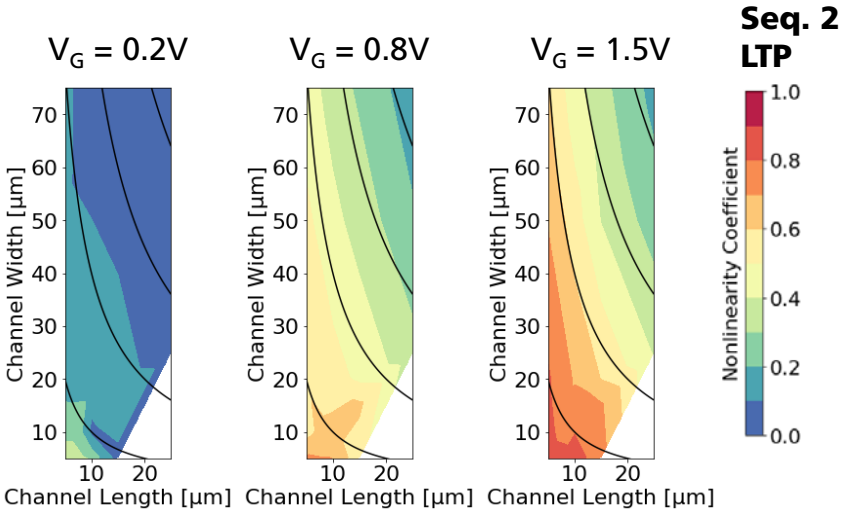
- Increase of nonlinearity with decreasing area
- More deviation for smaller devices? → Influence of width/length?



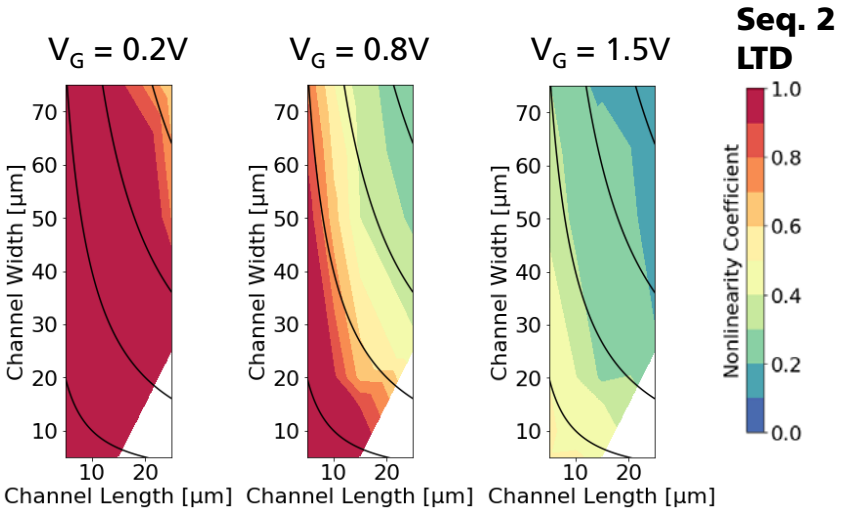


Influence of the device layout

- Seq2 W01 Potentation

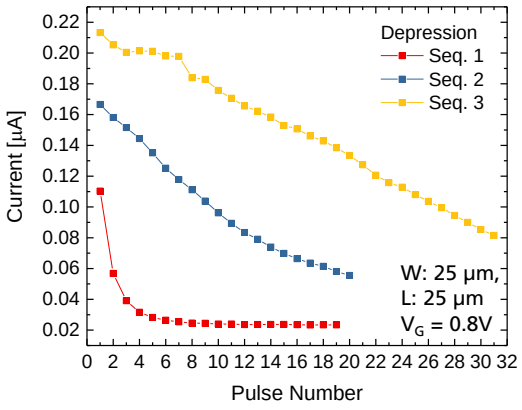


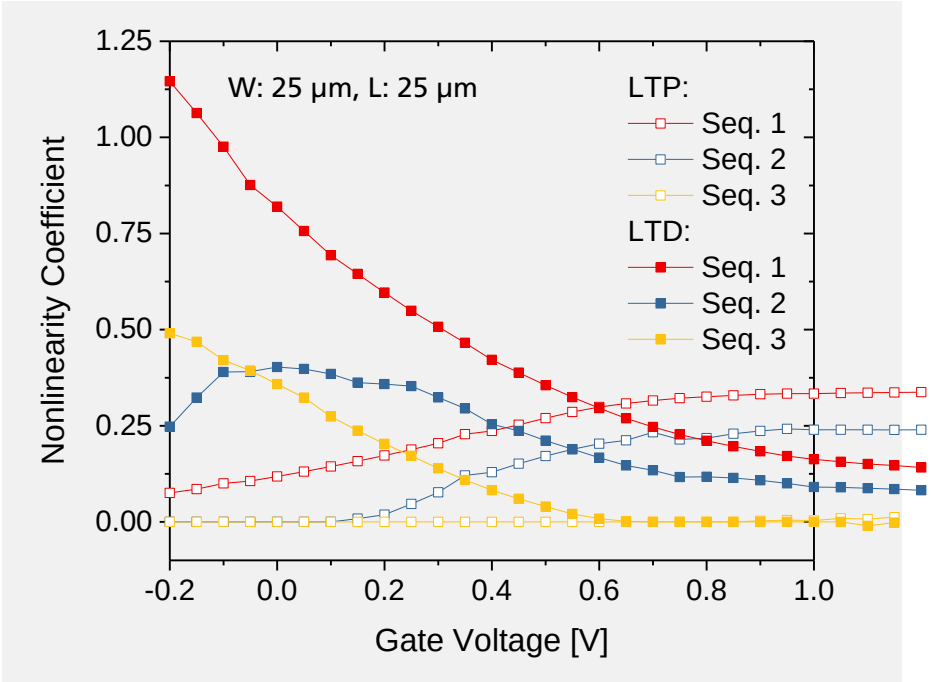
- Seq2 W01 Depression

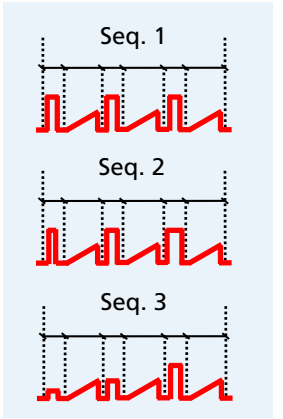


Sequence 1 – 3: Nonlinearity

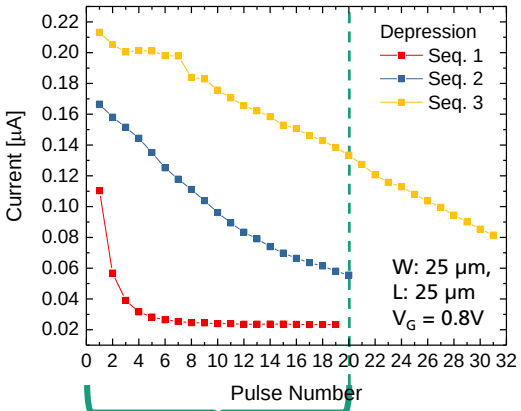
- Sequence 3 shows lowest nonlinearity



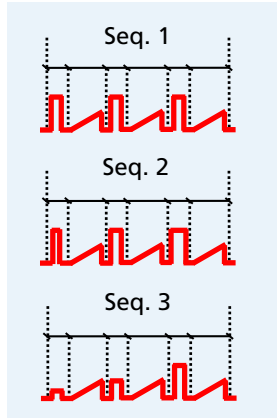


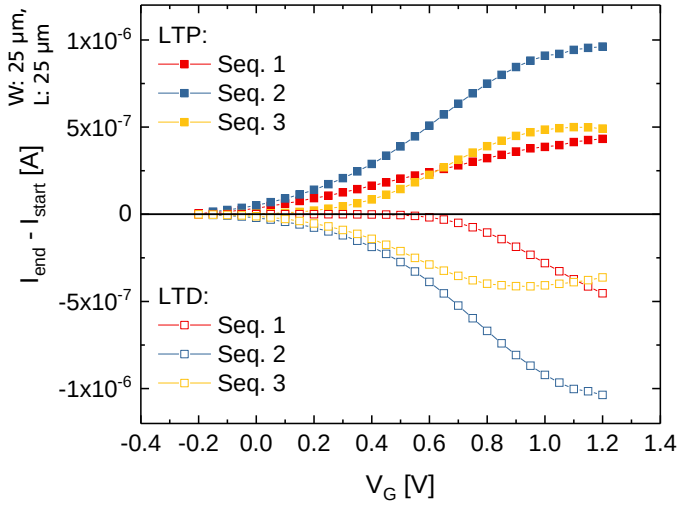


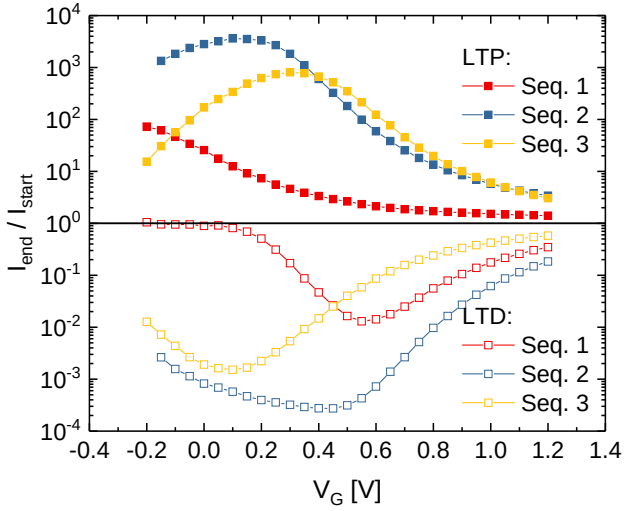
Sequence 1 – 3: Dynamic range (I_{on}/I_{off})



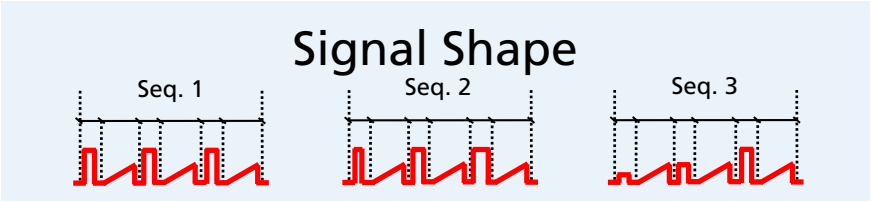
- Seq. 2 & 3 less asymmetric
- Higher variance for Seq. 2 & 3
- Dynamic range can be improved by using more pulses (Seq. 3)





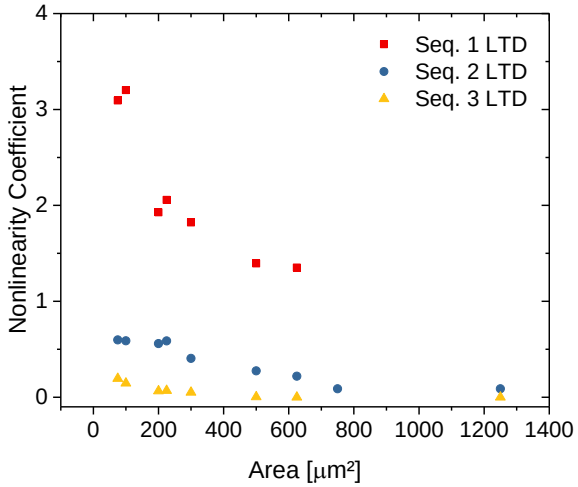


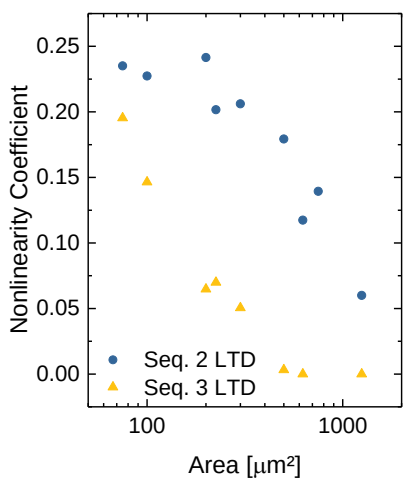
Sequence 1 – 3: Area Scaling

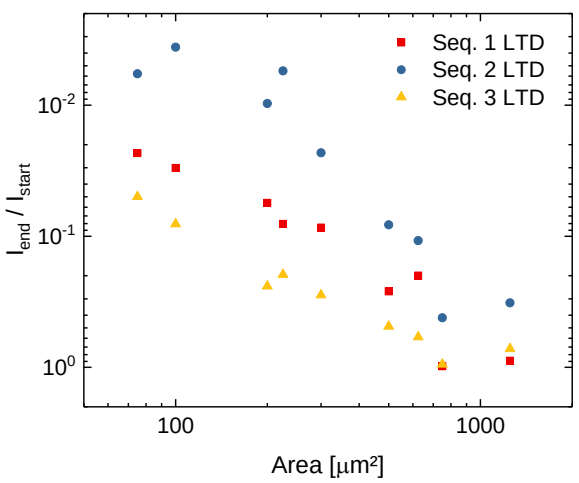


- Seq. 1 shows a very rapid increase in nonlinearity with area scaling
- Seq. 2 and 3 show slower increase, could be used for smaller devices

- Origin lies in domain structure and nucleation limited switching

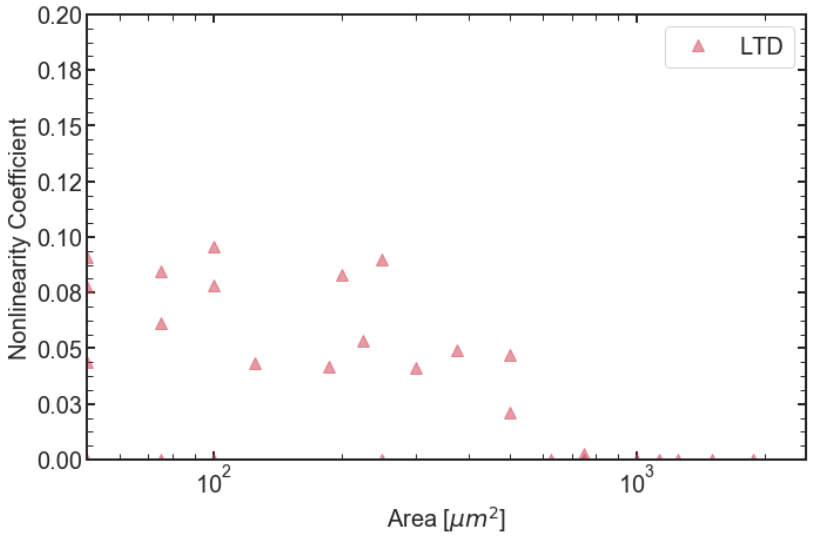


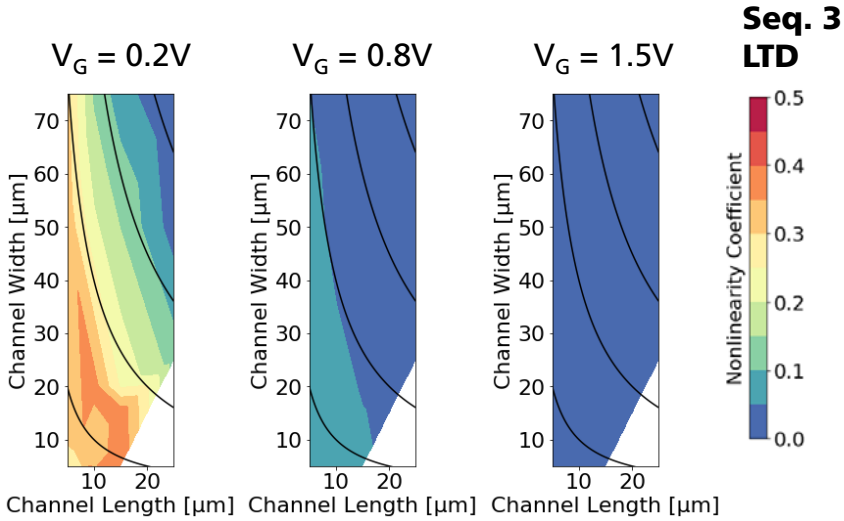


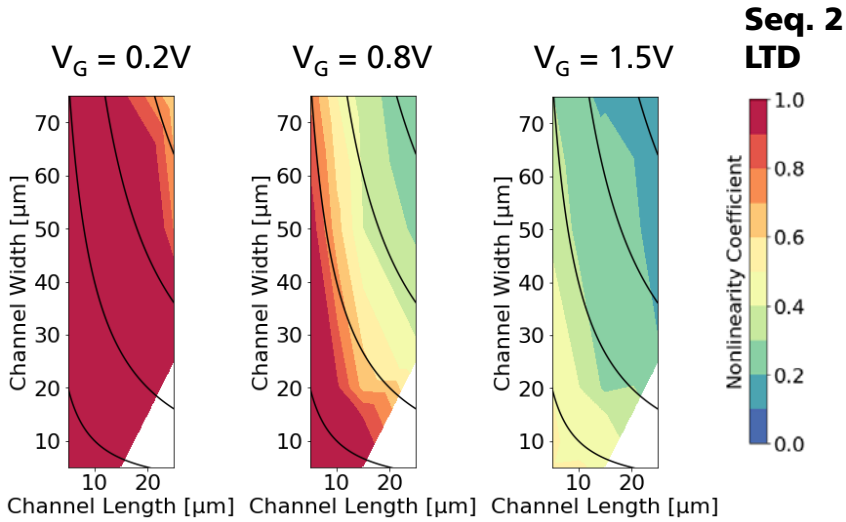


Sequence 1 – 3: Area Scaling

- Seq. 3 shows the same trend as seq. 2
- Much lower nonlinearity for seq. 3 even for the smaller devices







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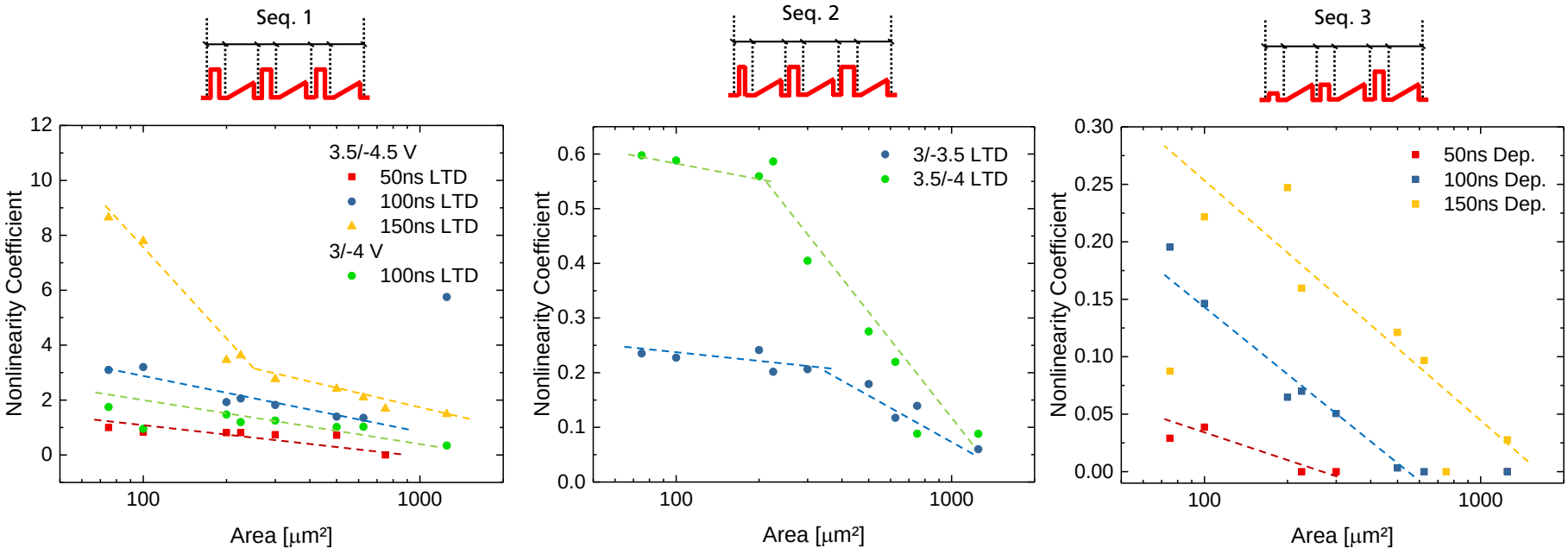
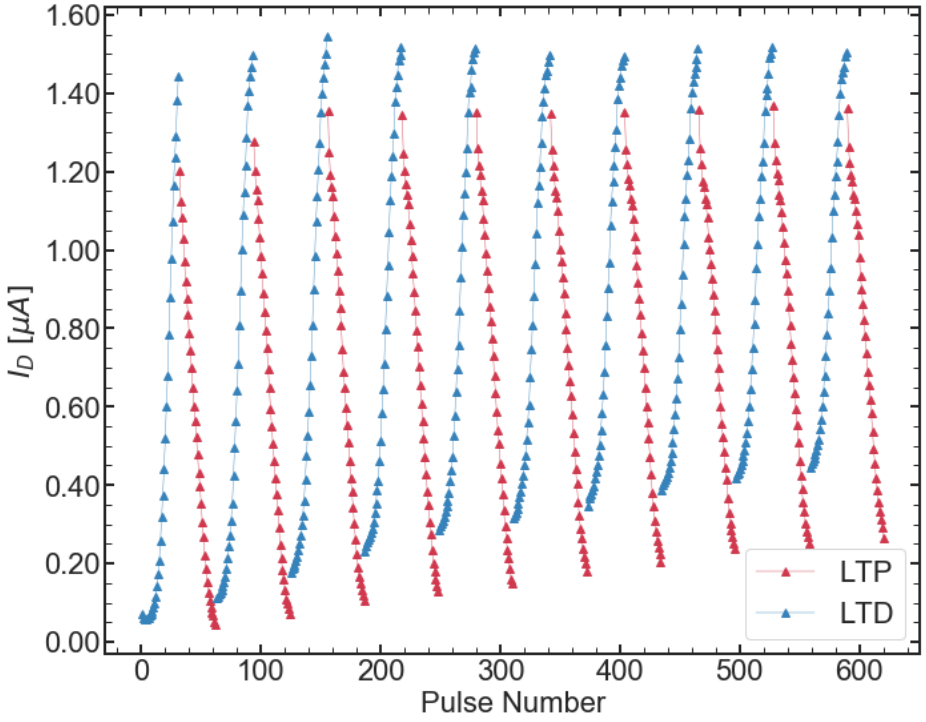
Sequence 1 – 3: Possible Adjustments for Area Scaling

- Adjusting signal shape for smaller devices improves nonlinearity



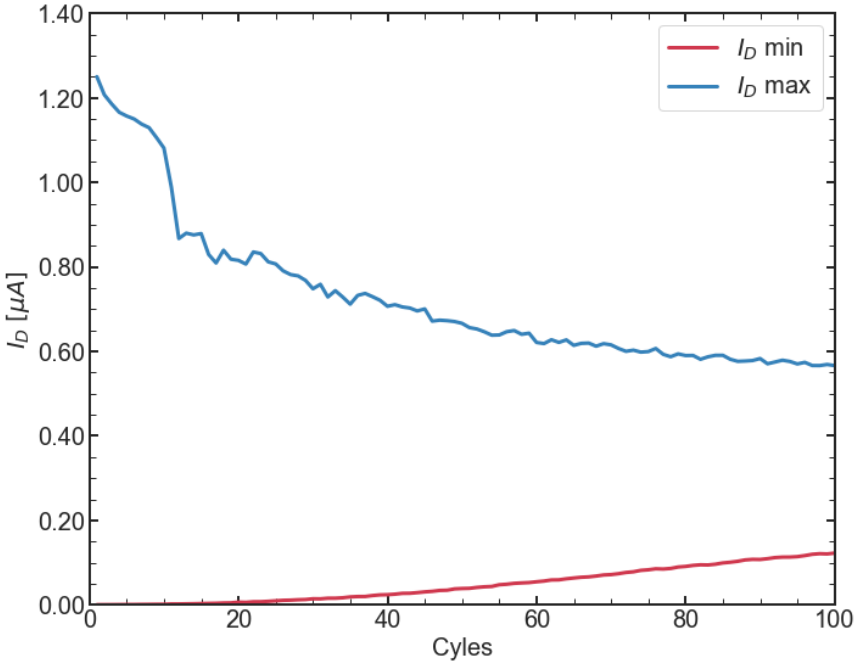
Endurance of Intermediate States

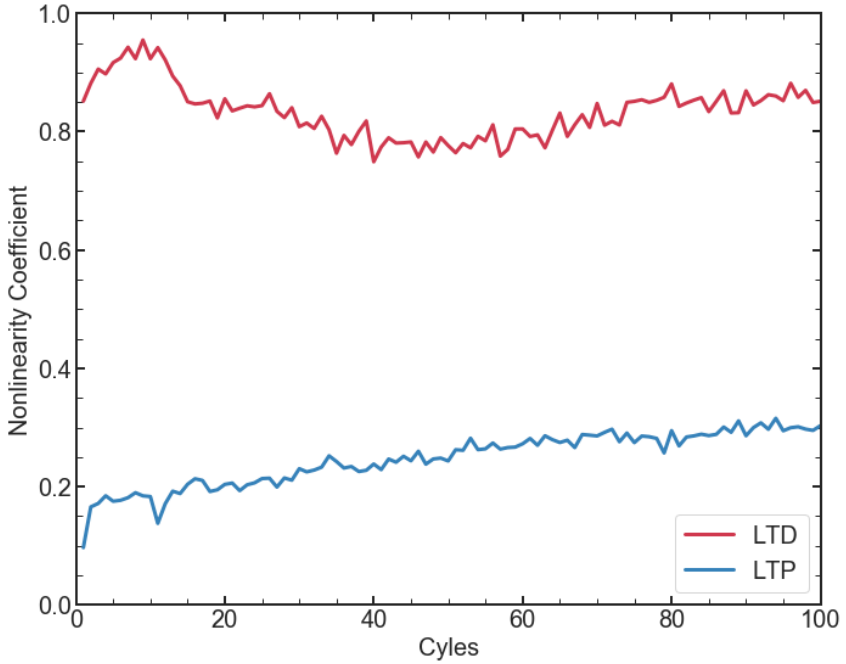
- Sequence 3 shows slight degradation during 600 pulses (20 cycles)
- Increasing asymmetry between LTP and LTD
- Nonlinearity does not deviate strongly during 100 cycles



Endurance of Intermediate States

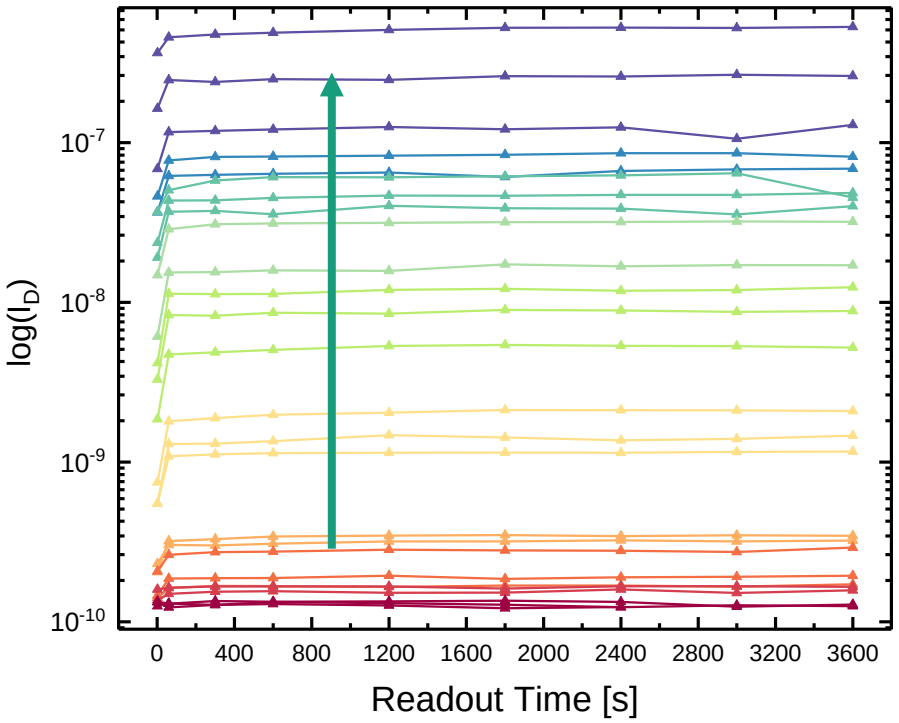
- Sequence 2 shows slight degradation during 4000 pulses (100 cycles)
- Nonlinearity does not deviate strongly during 100 cycles

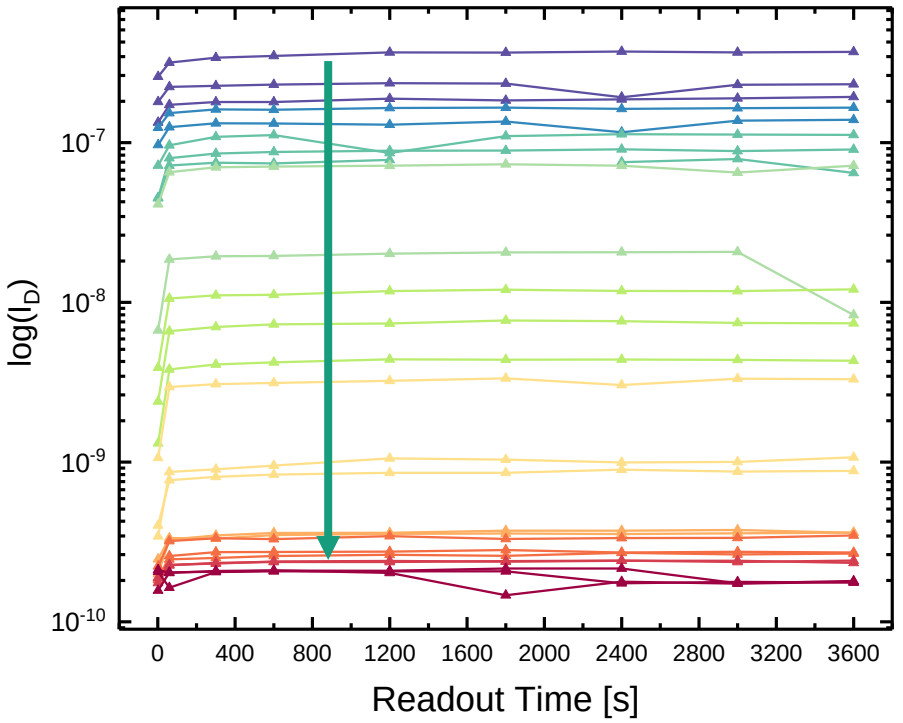




Retention of Intermediate States

- No retention loss for a readout time up to 1 h





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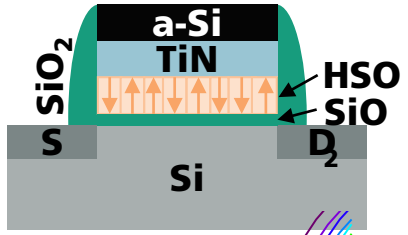
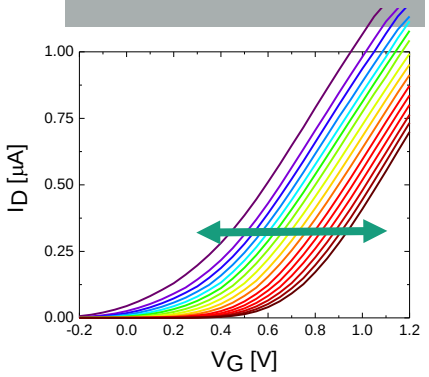
Conclusion & Outlook

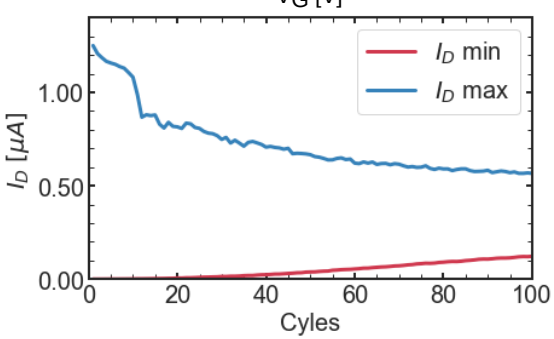
- Nonlinearity and dynamic range can be tuned by signal shape and gate voltage
- Scaling of area without strong increase in nonlinearity possible for sequence 2 and 3
- Device layout influences nonlinearity

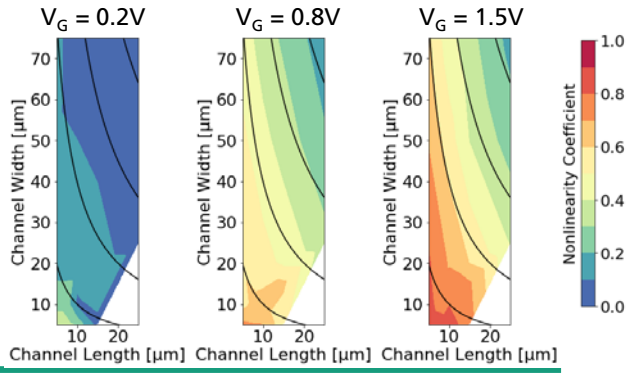
- Good retention during 1h measurement
- Slight degradation during 4000 pulses for sequence 2

➢ FeFETs can be tuned for certain applications

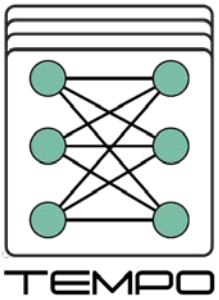






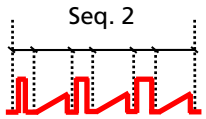


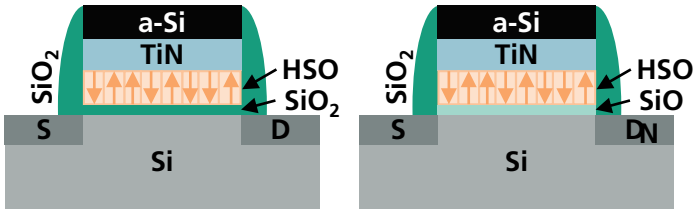
Acknowledgements



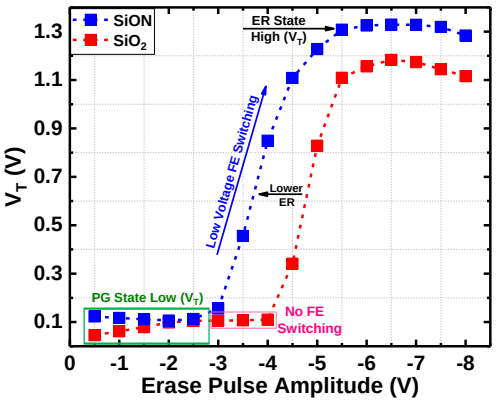
We received funding within the ECSEL Joint Undertaking project TEMPO in collaboration with the European Union's H2020 Framework Program (H2020/2014-2020) and National Authorities, under grant agreement number 783176.

FeFET SiO2 vs SiON

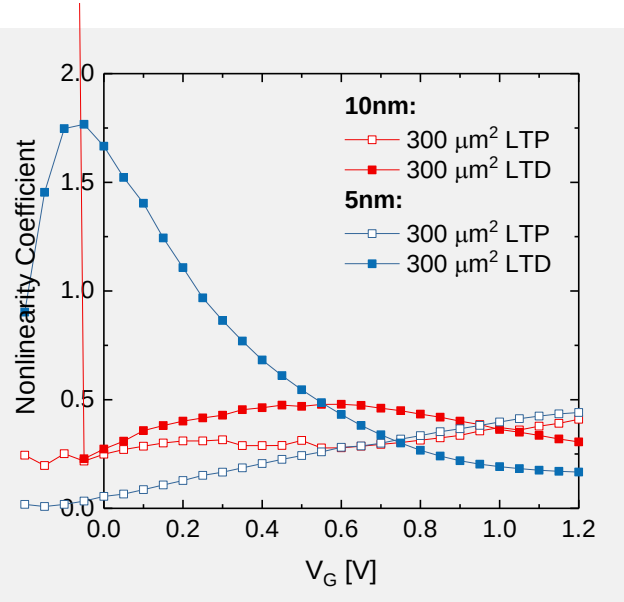


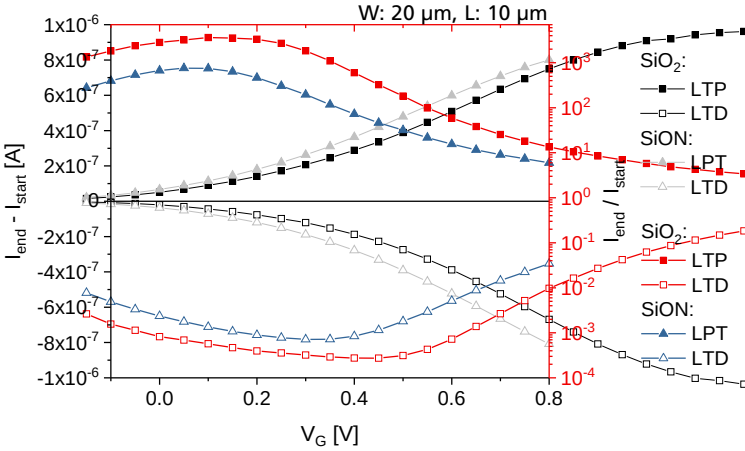


- SiON: Lower voltages necessary to switch fully → Increase in nonlinearity

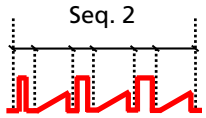


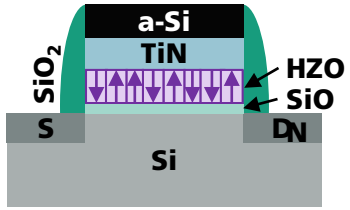
T. Ali et al., TED (2018)

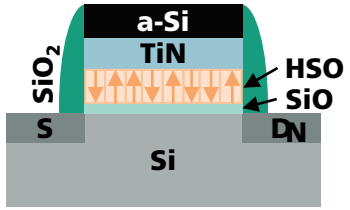




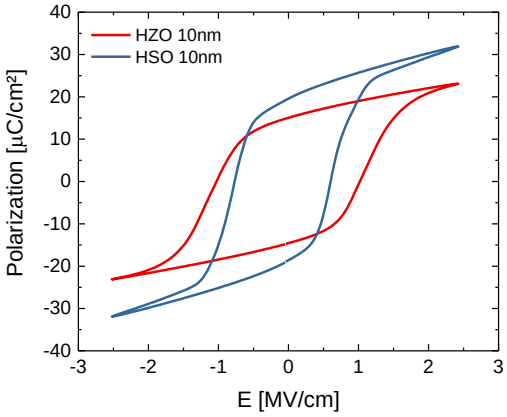
FeFET HSO vs HZO

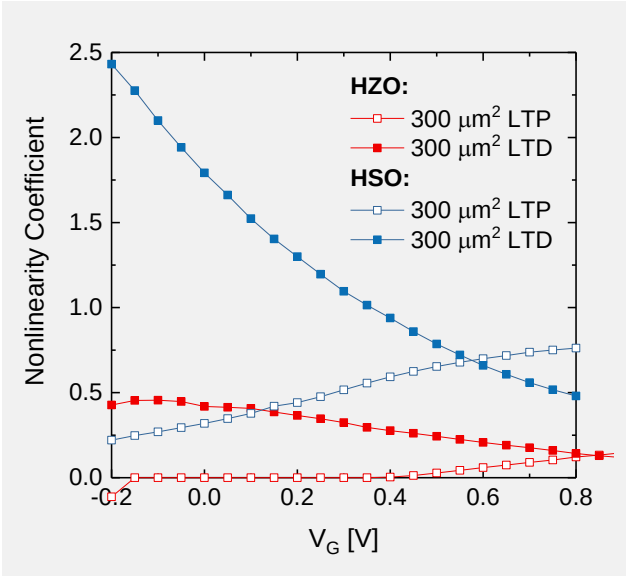


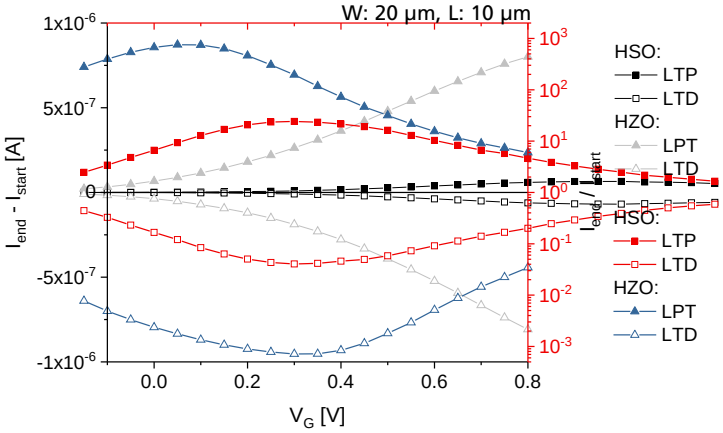




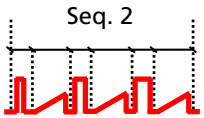
- Lower Variance due to larger MW (FeFET Comparison) not reaching saturation current
- More Subloop Behaviour → Lower nonlinearity coefficient

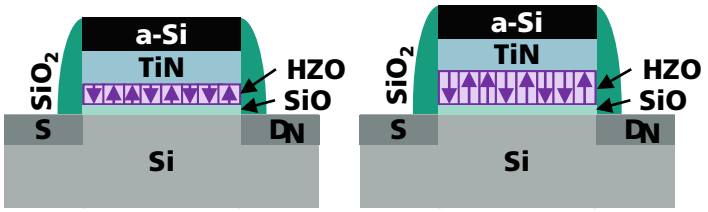




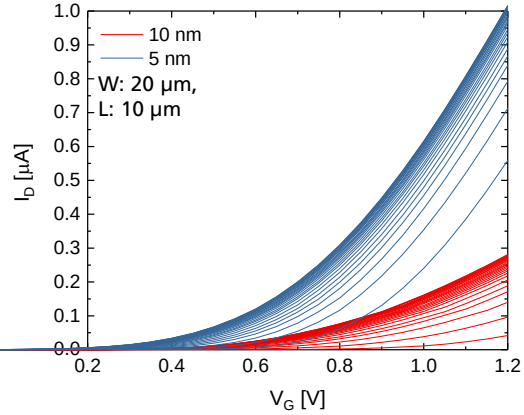


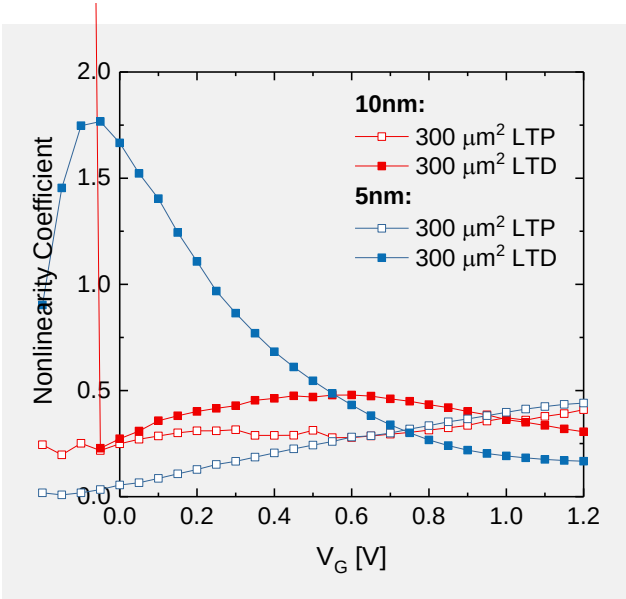
FeFET thickness influence

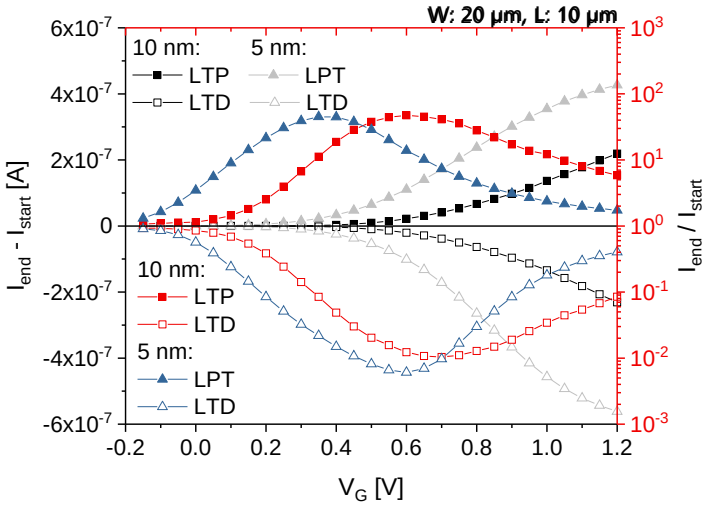




- Thinner film results in an increased electrical field → Compressed / steeper behaviour with V_G



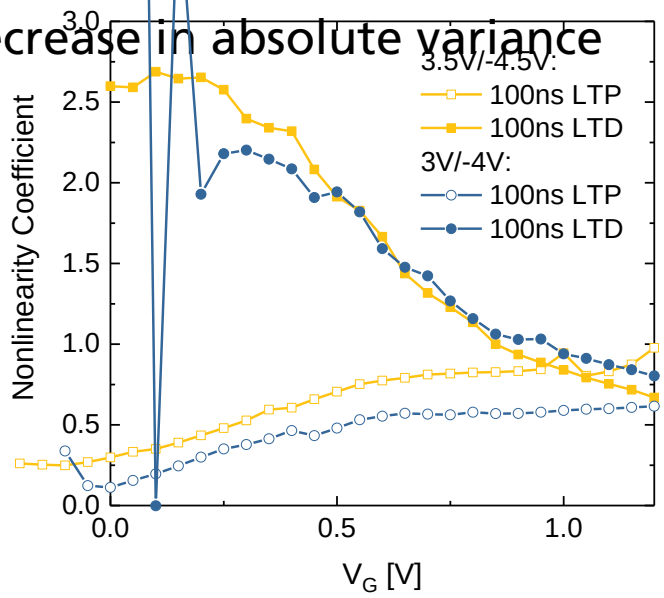


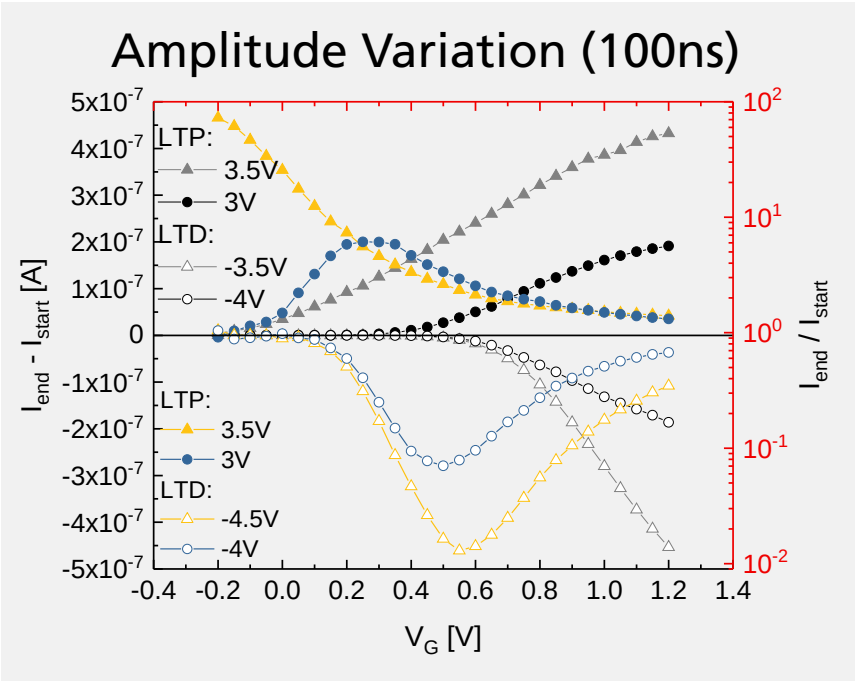


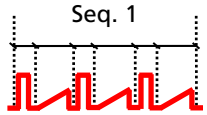
Sequence 1: Pulse Amplitude

Amplitude reduction:

- Decrease of nonlinearity in potentation
- Reduced assymetry of the variance
- Decrease in absolute variance

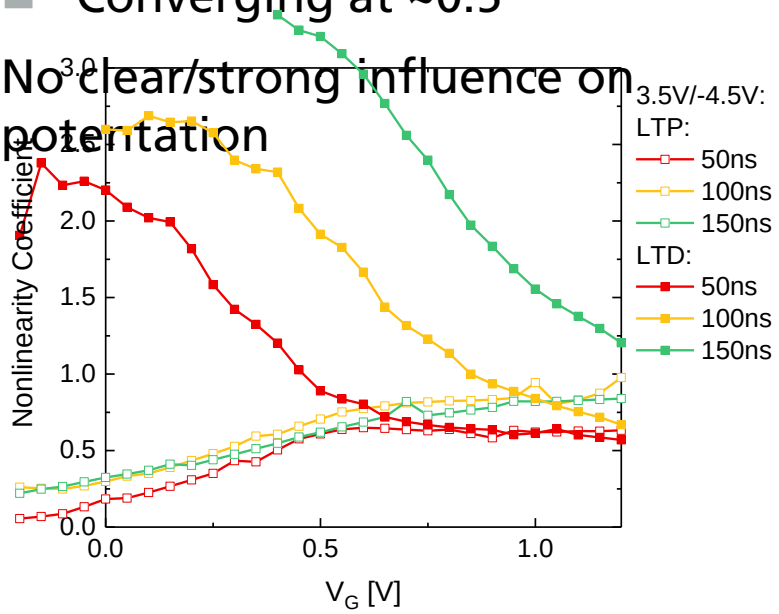


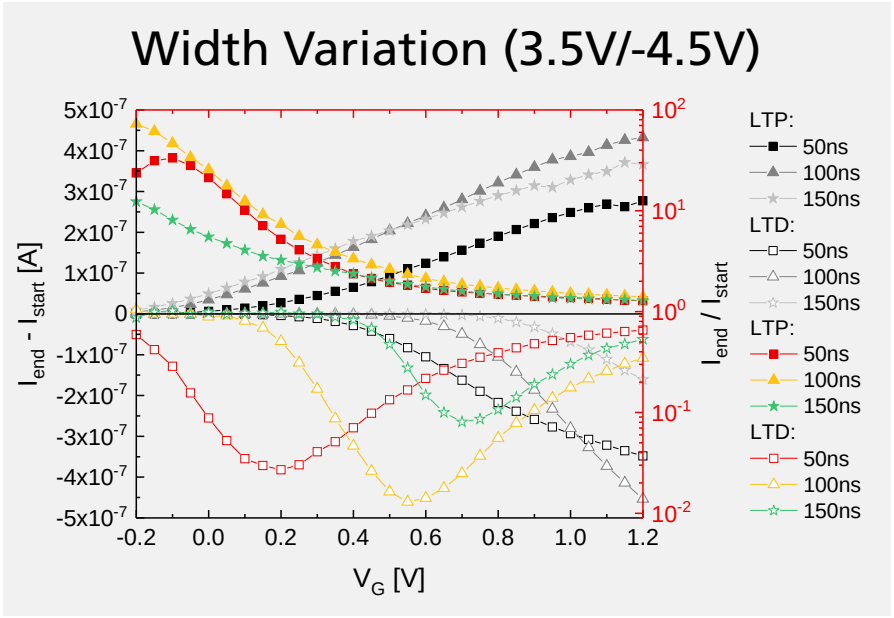




Sequence 1: Pulse Width

- Strong effect on depression
  - Moving to lower VG
  - Converging at ~0.5
- No clear/strong influence on potentiation

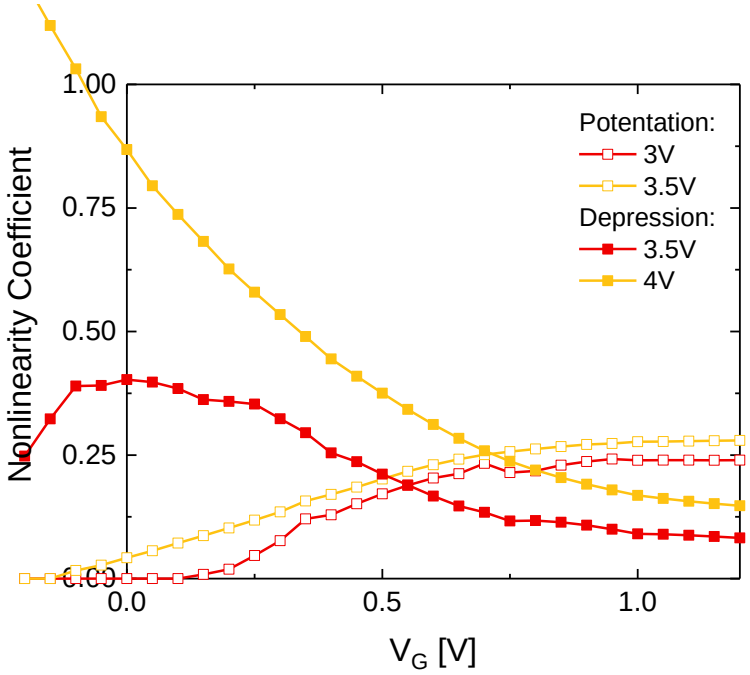


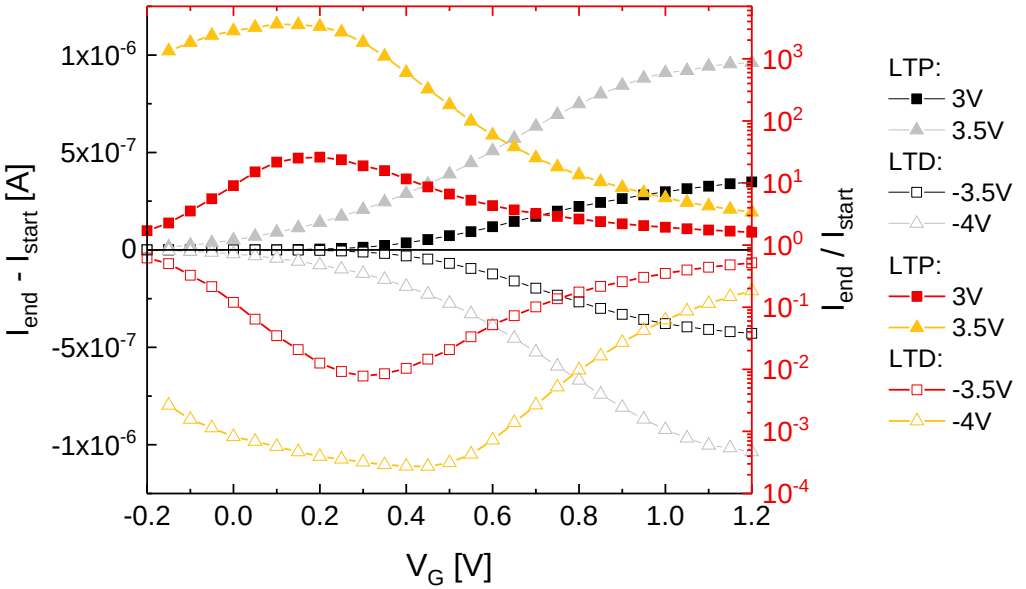


Fraunhofer IPMS

Sequence 2: Pulse Amplitude

- Trade-off between nonlinearity and variance





Sequence 3: Pulse Width

- Longer pulses increase slope of nonlinearity
- Absolute variance reaches maximum for 100ns
- Variance improvements with higher number of pulses