Influences on the nonlinearity of ferroelectric synapses for neuromorphic computing

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Influences on the nonlinearity of HfO_2 based ferroelectric synapses (FeFETs) for neuromorphic computing

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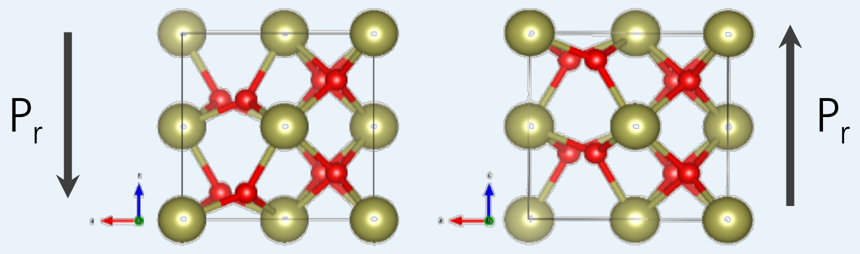
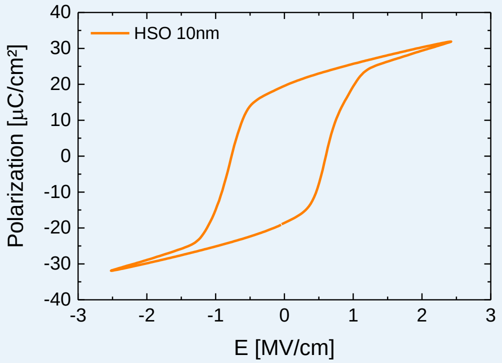
Ferroelectric Fieldeffect Transistor (FeFET)

Ferroelectricity in HfO_2

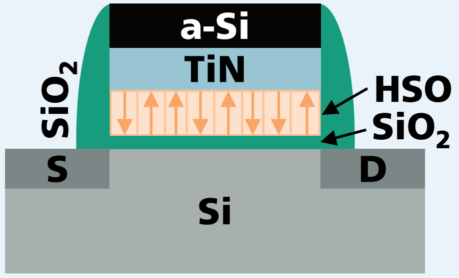
Orthorhombic ($Pca2_1$)

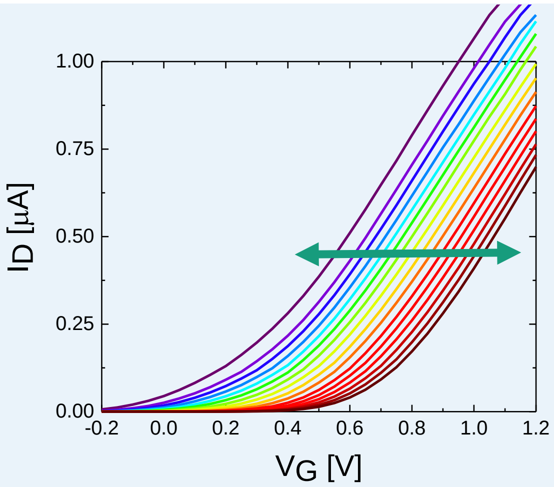


- Stabilized by Dopants, Stress, …

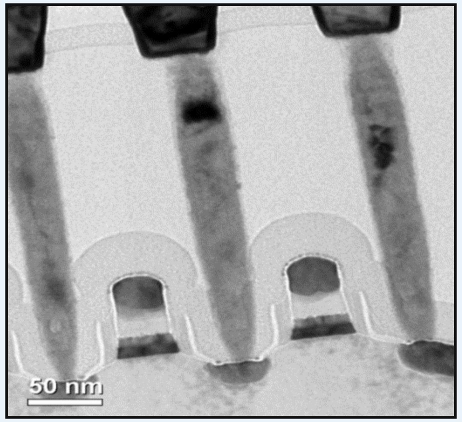


FeFET Gate Stack





28nm Proof of Concept



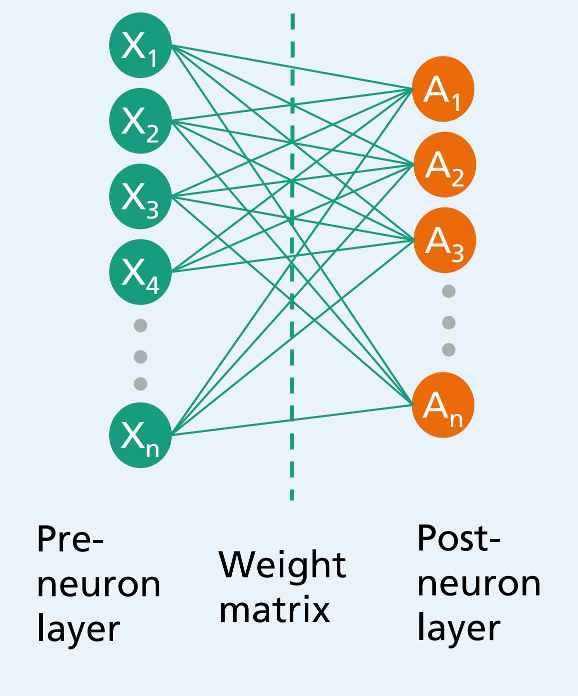
- Gate-First
- ΔV_T = 1-1.2 V
- ±5V, < 100 ns
- 10^4 endurance
- 10y retention

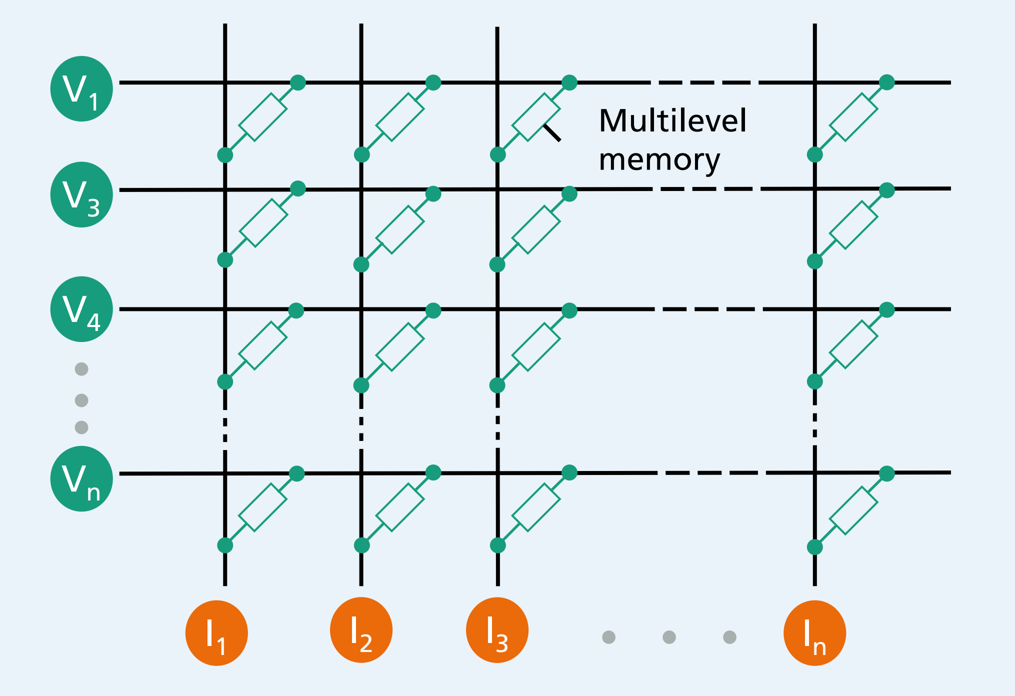
J. Müller et al., VLSI (2012)

Neuromorphic Computing

Dot-product engine

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





Non-Linearity Coefficient

1. Nonlinearity Fit:

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

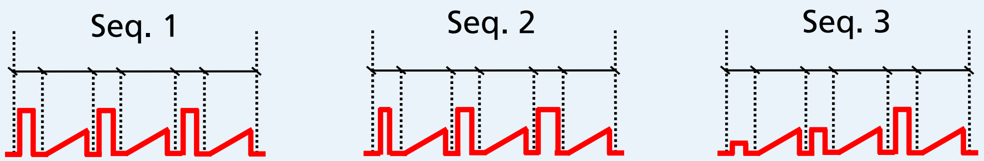
P := Pulse Number
D := Start Pulse Number

2. Nonlinearity Coefficient:

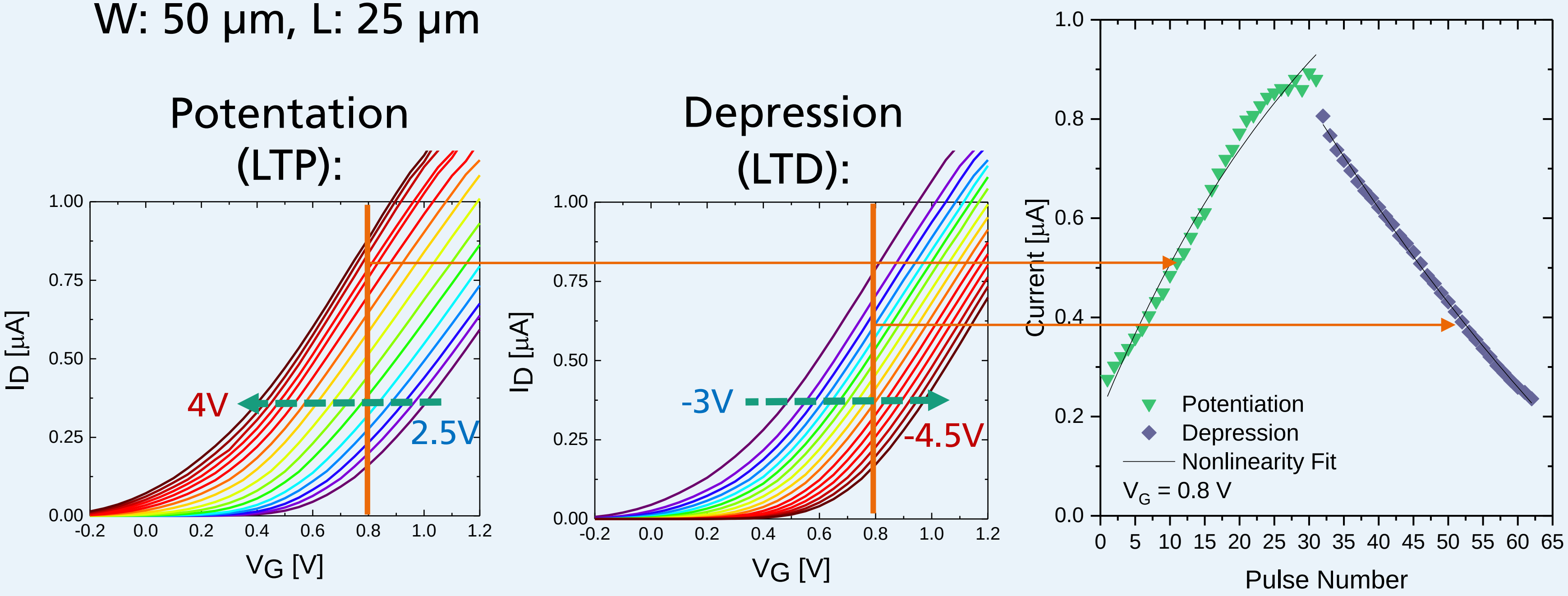
$$\alpha_{p,d} = \frac{1.726}{A + 0.162}$$

M. Jerry et al., IEDM (2017)

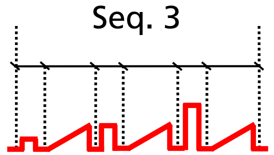
Signal Shape



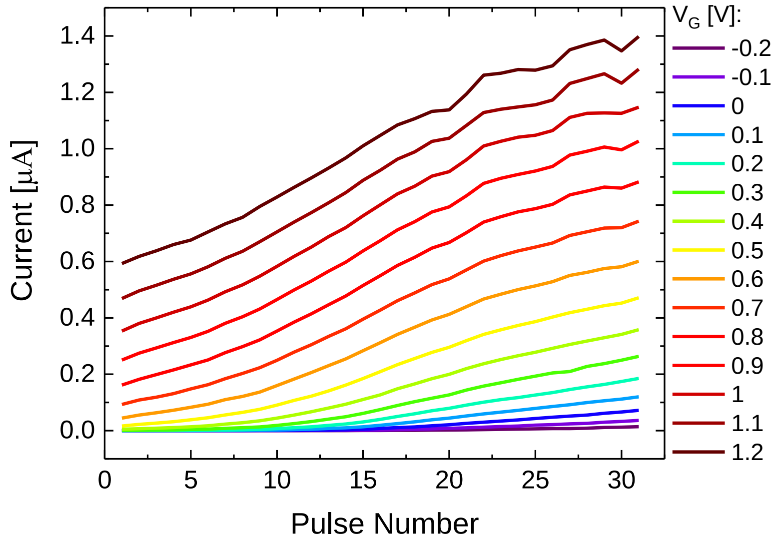
Seq. 3: 150ns
W: 50 µm, L: 25 µm

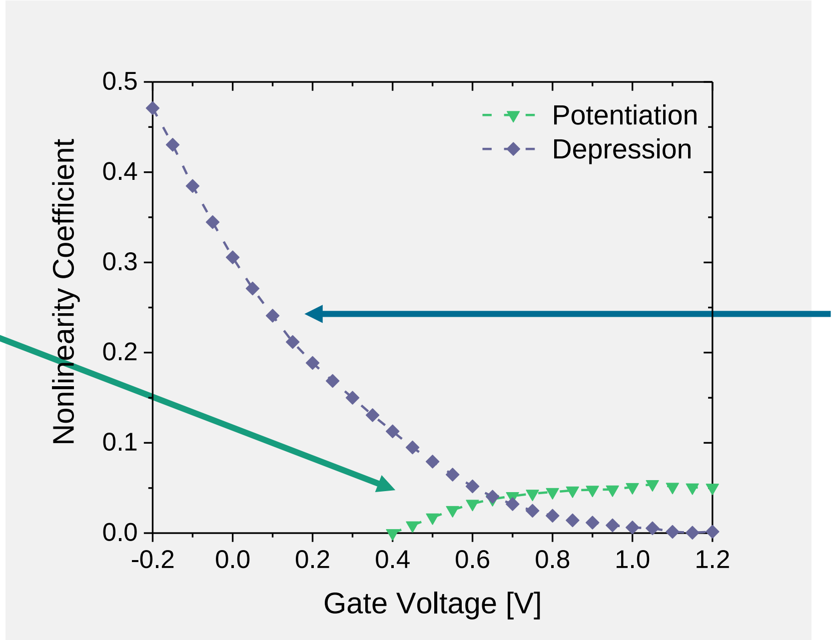


Influence of the Gate Voltage

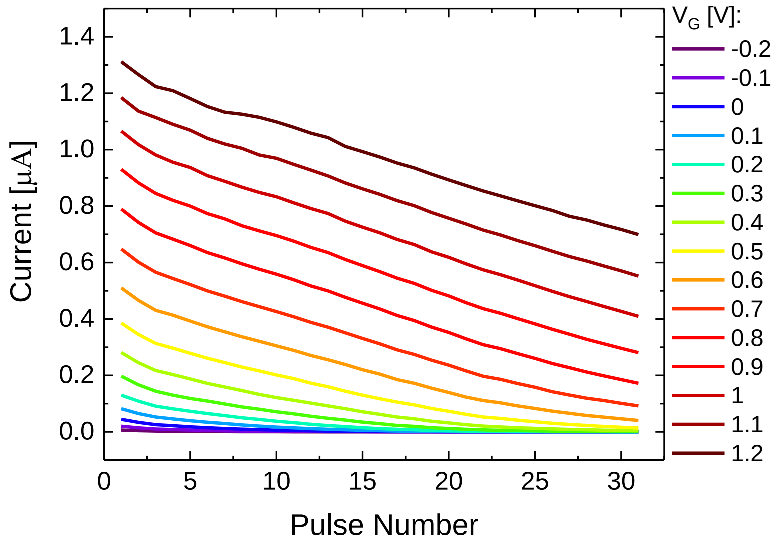


Potentation:





Depression:



- Nonlinearity is strongly dependent on gate voltage

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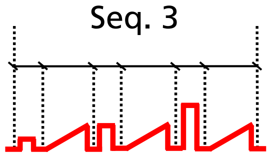
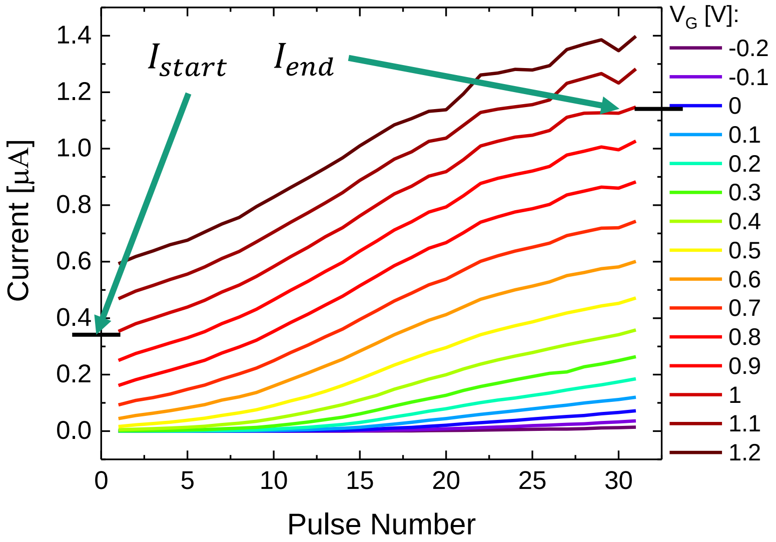
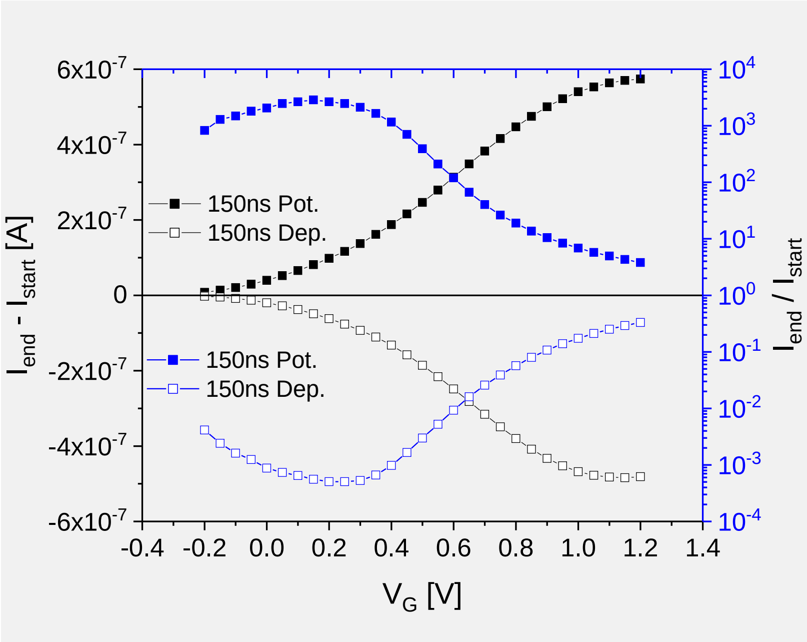
Influence of the Gate Voltage

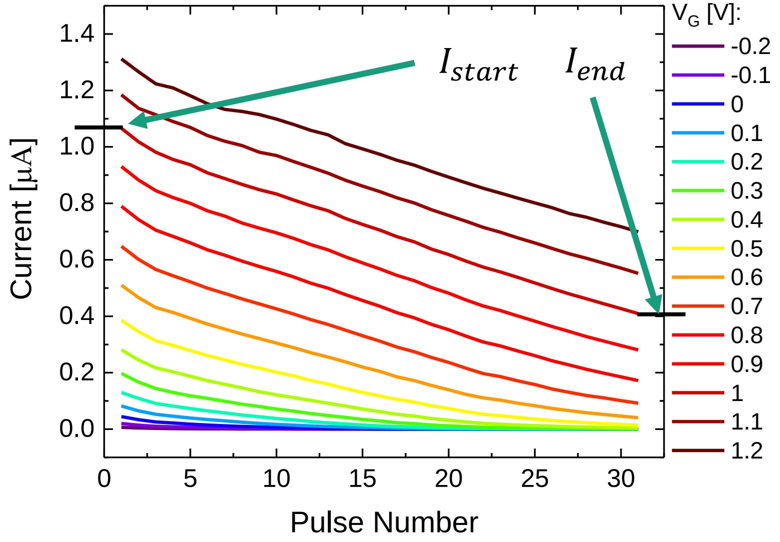


Potentation:





Depression:



- Variance strongly dependent on gate voltage
- Relative and absolute variance show maximum at different gate voltages

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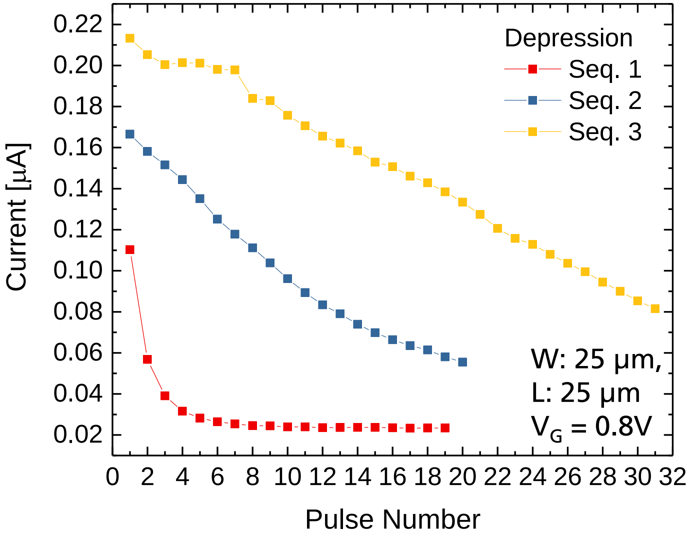
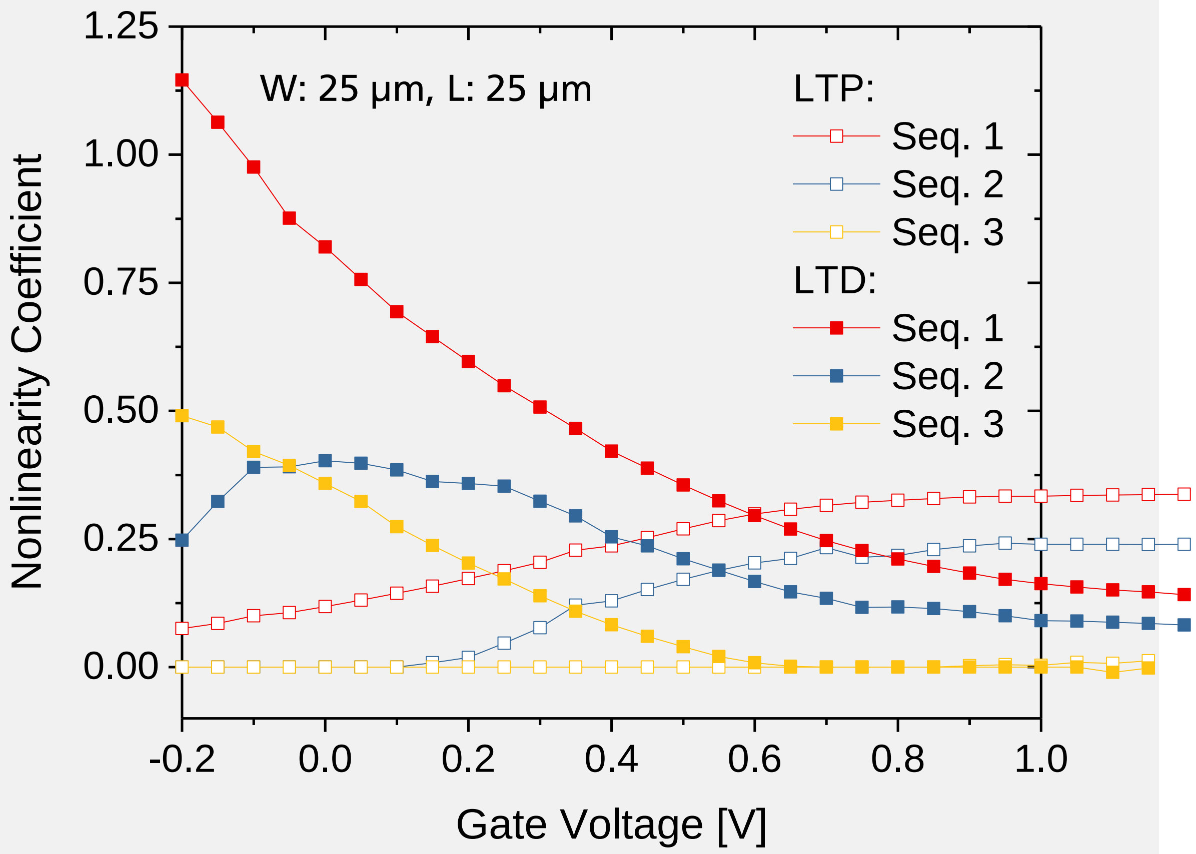
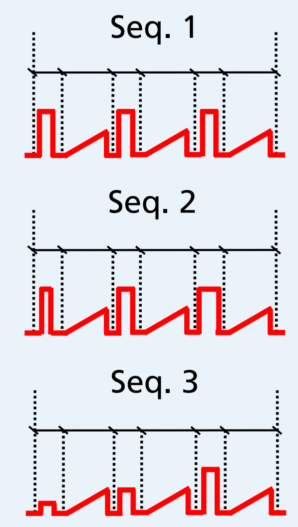
Sequence 1 – 3: Nonlinearity

- Sequence 3 shows lowest nonlinearity







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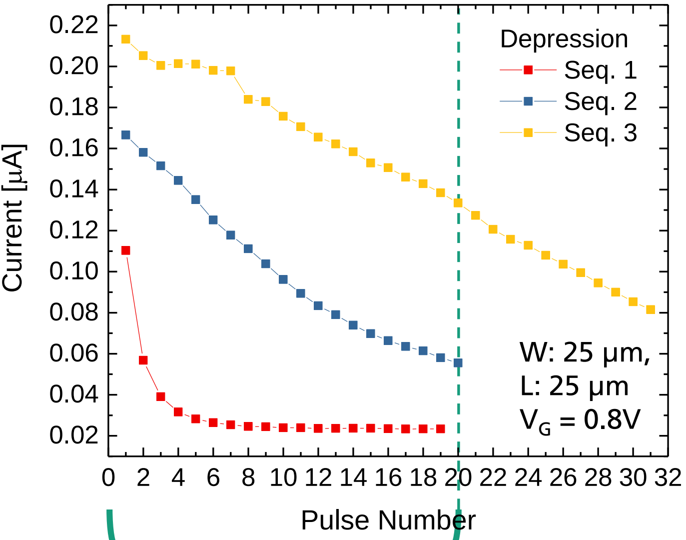
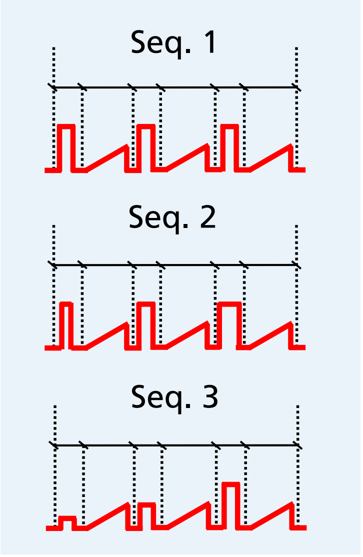
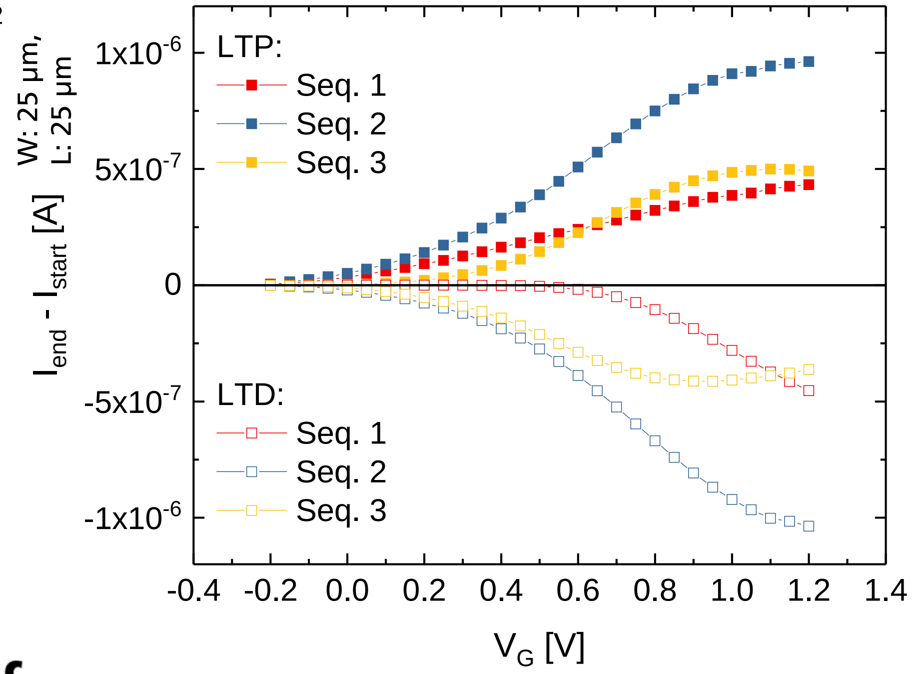
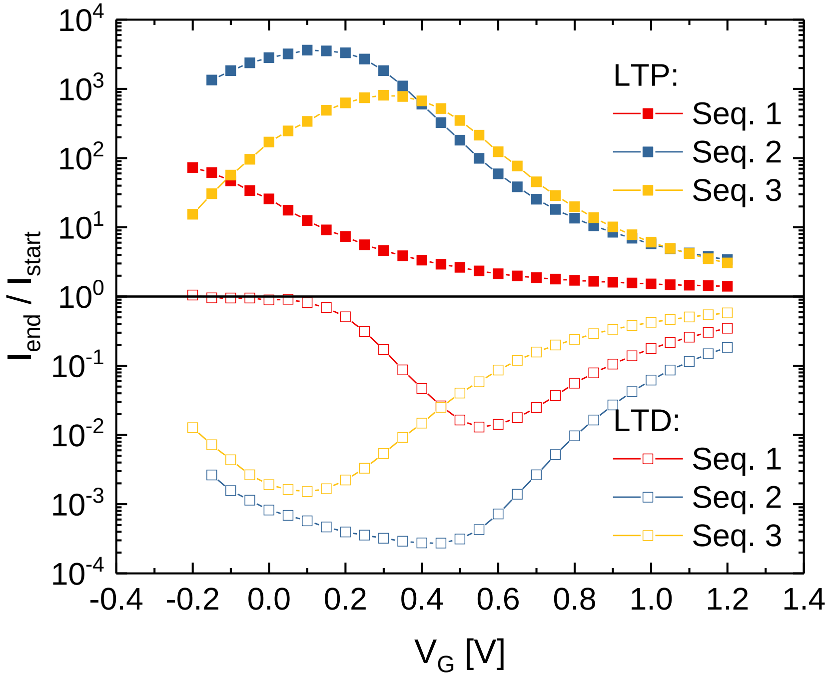
Sequence 1 – 3: Variance (I_{on}/I_{off})



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







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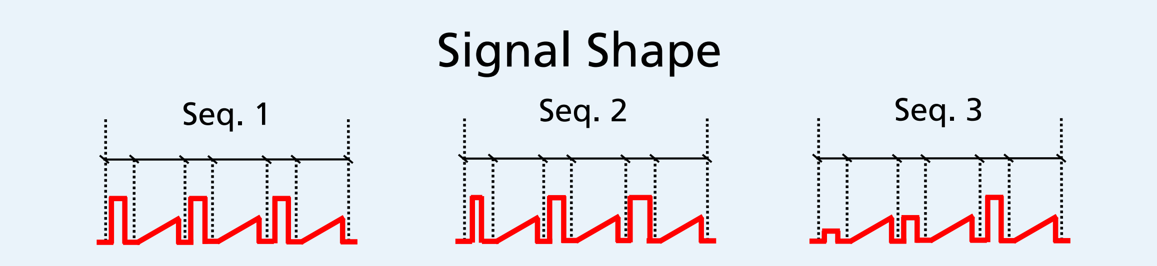
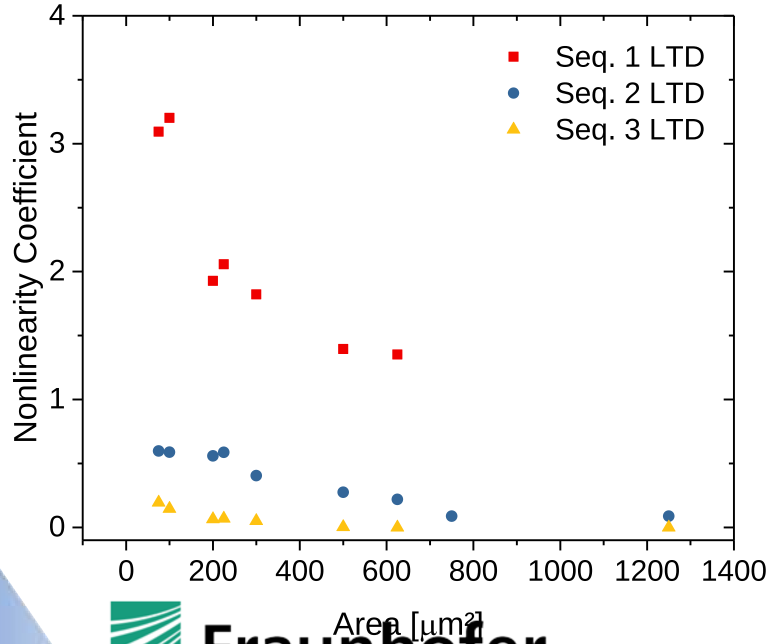
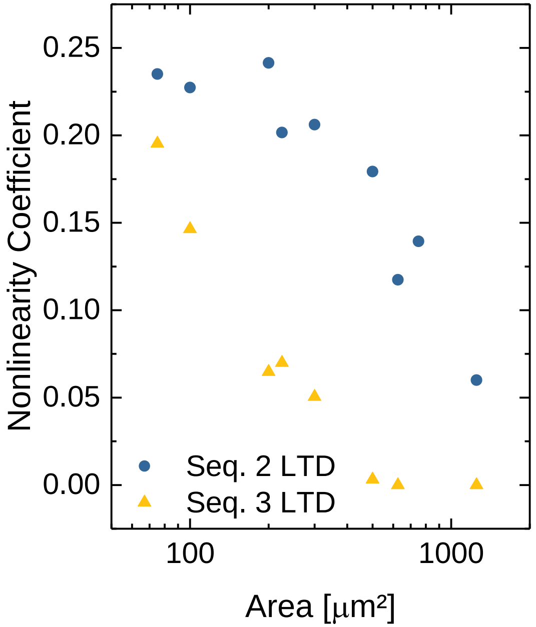
Sequence 1 – 3: Area Scaling

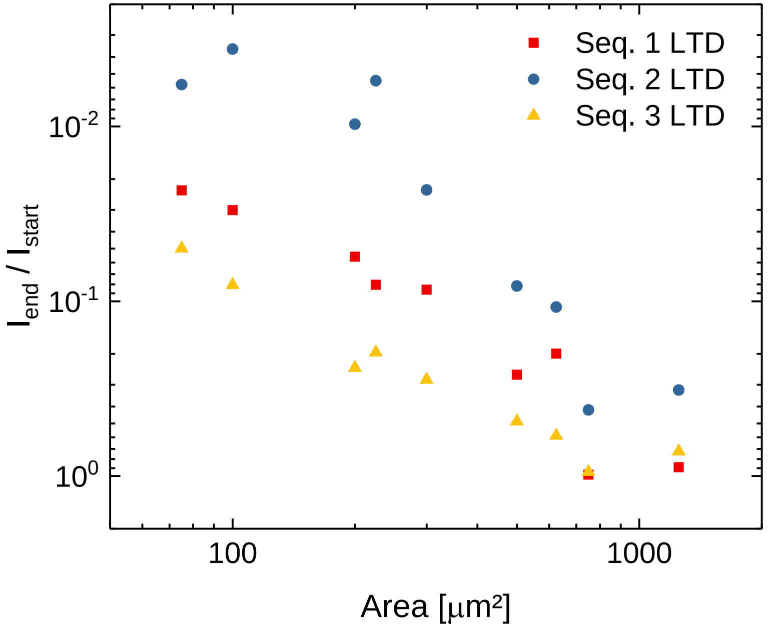


- Seq. 1 shows a very rapid increase in nonlinearity with area scaling
- Seq. 2 and 3 show slower increase, could be used for smaller devices

- Origin lies in domain structure and nucleation limited switching







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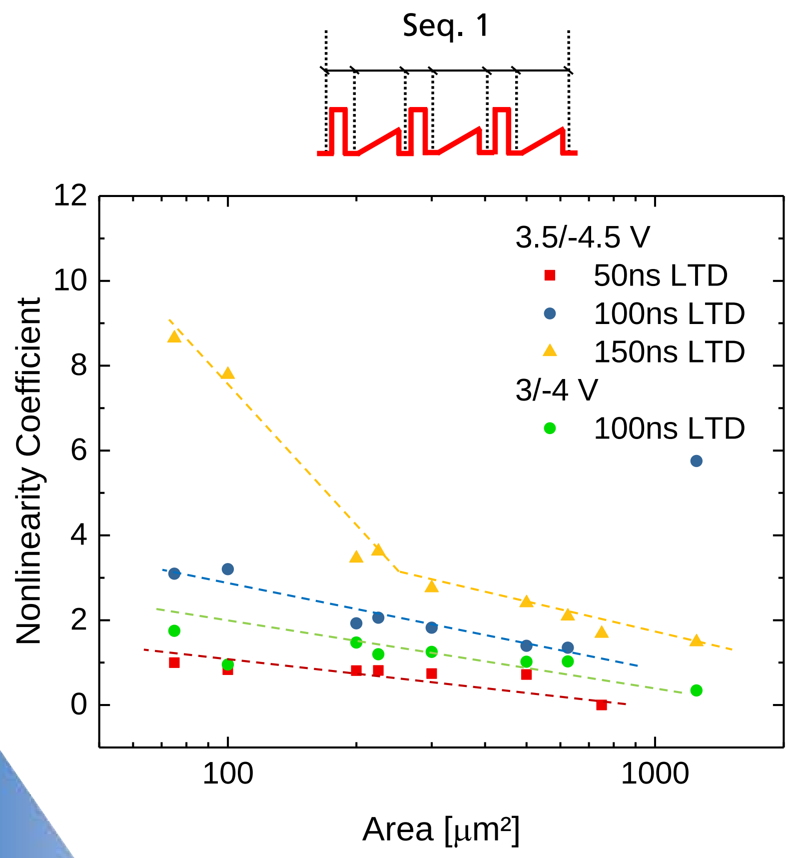
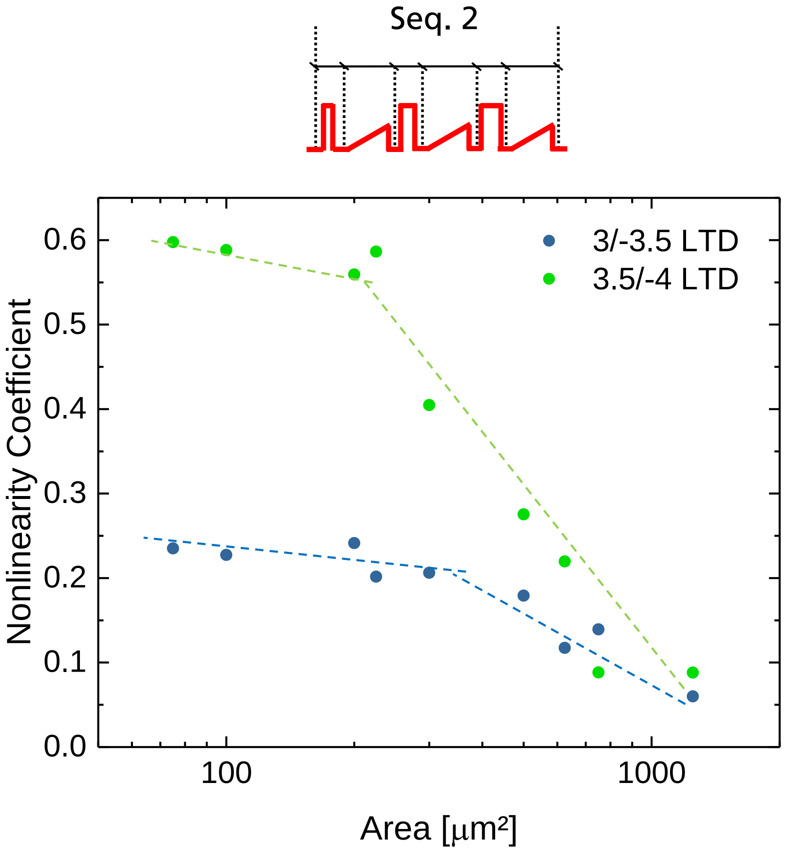
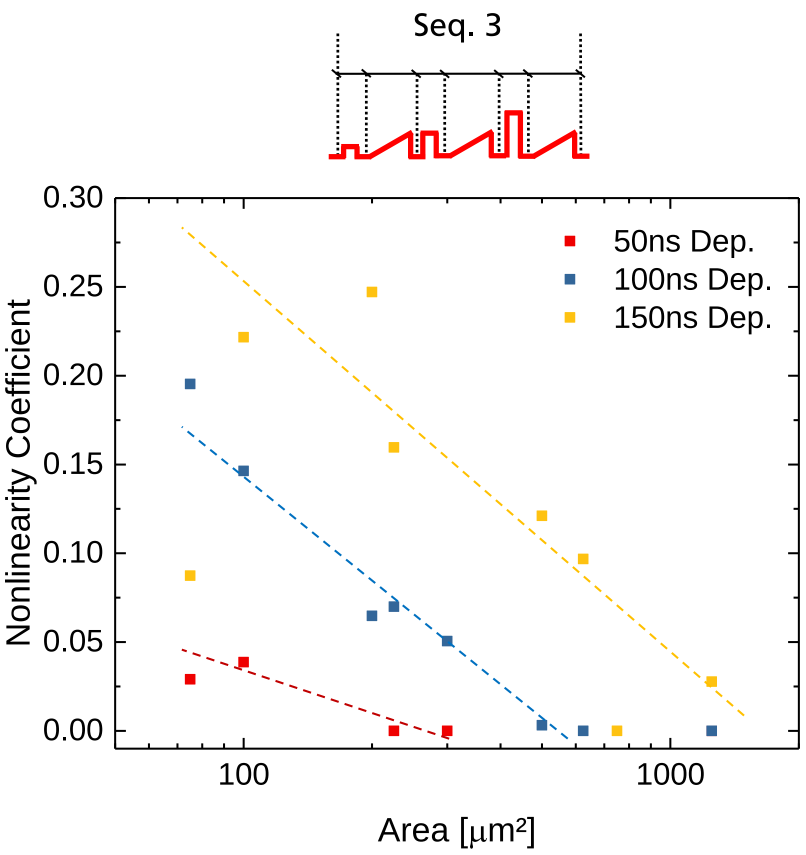
Sequence 1 – 3: Possible Adjustments for Area Scaling

- Adjusting signal shape for smaller devices improves nonlinearity







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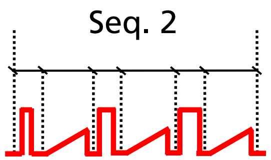
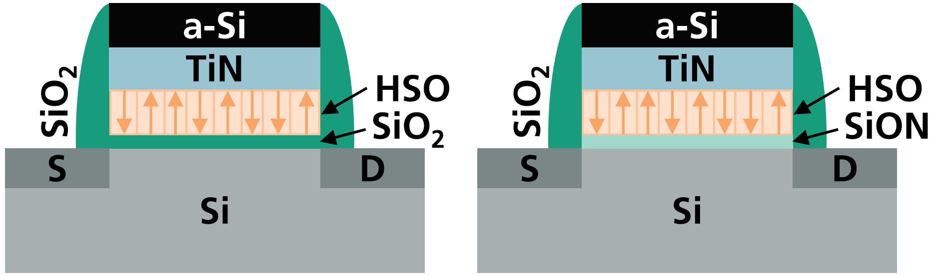
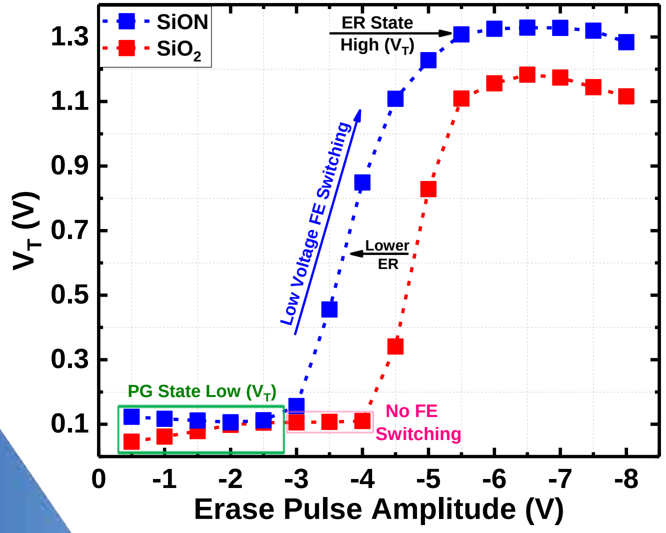
FeFET SiO2 vs SiON

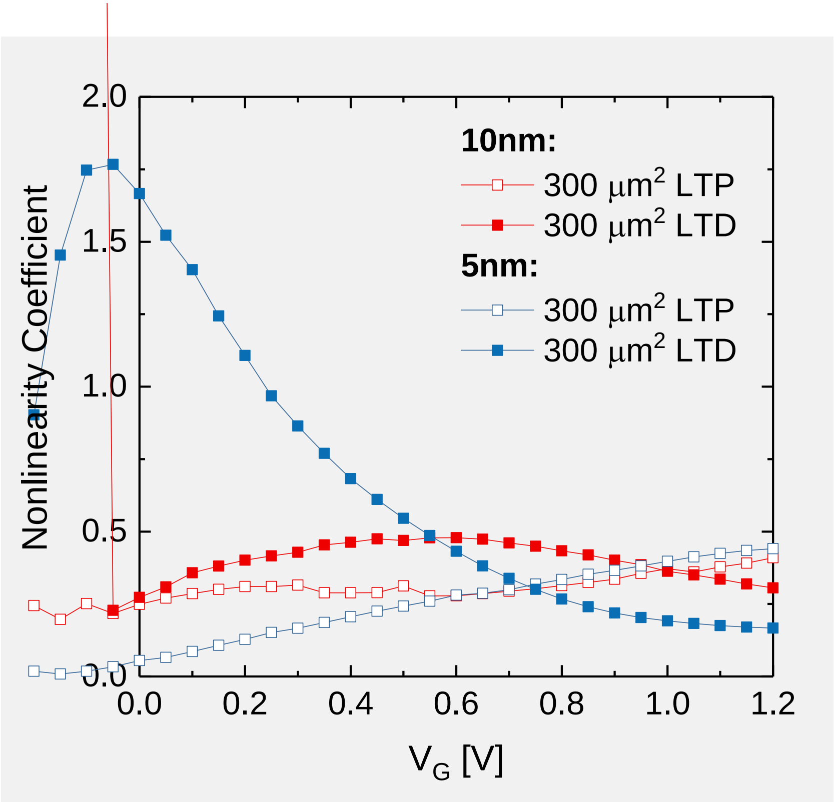


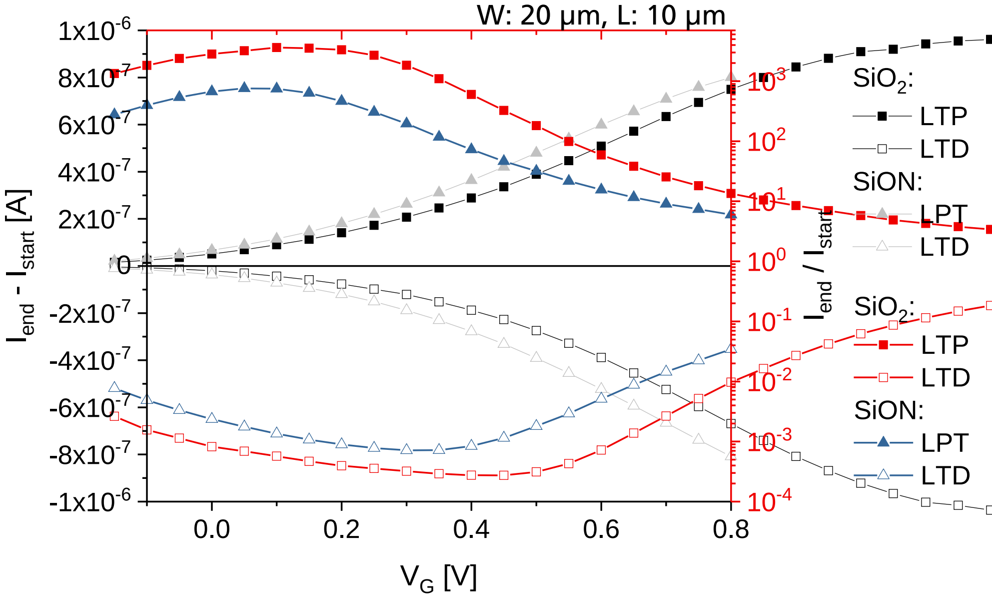


- SiON: Lower voltages necessary to switch fully → Increase in nonlinearity

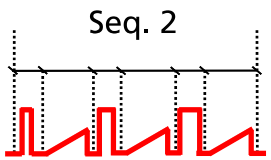


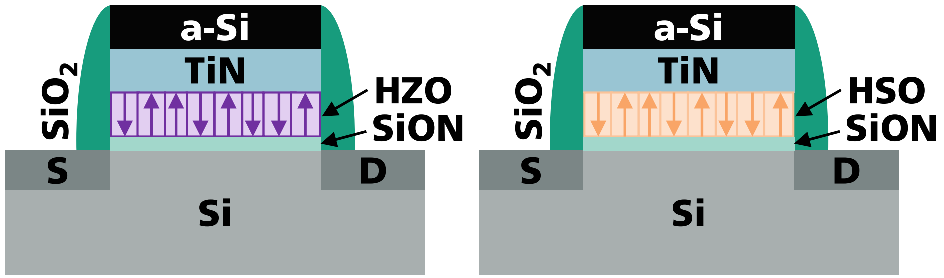
T. Ali et al., TED (2018)



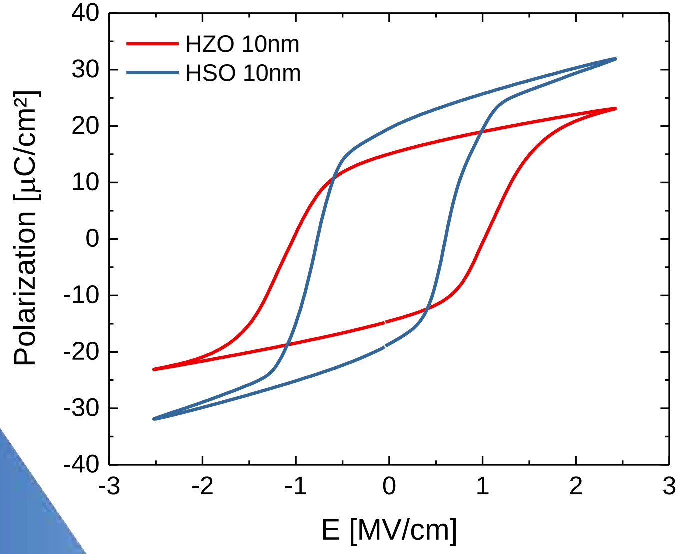


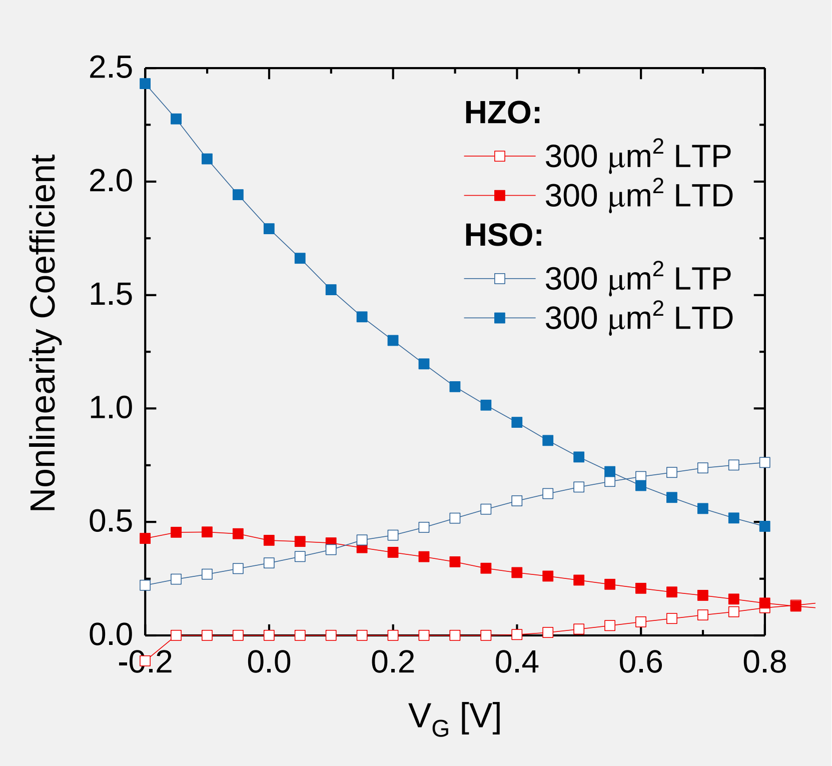
FeFET HSO vs HZO

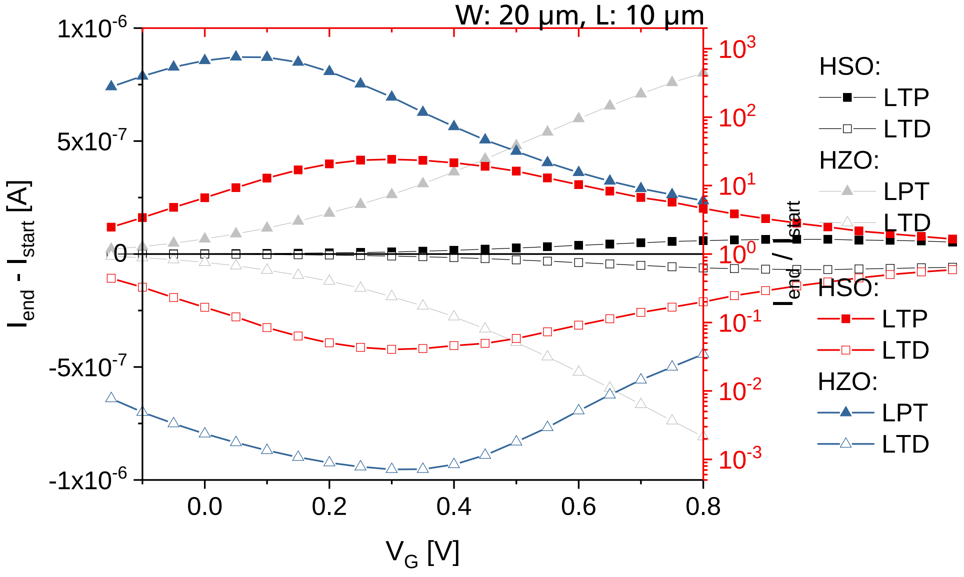




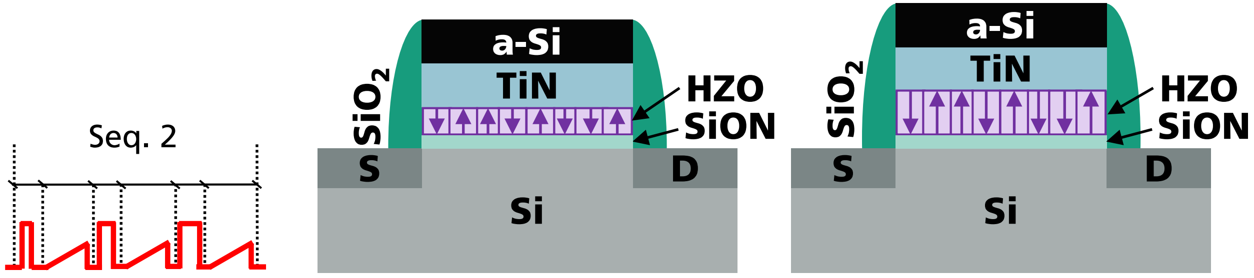
- Lower Variance due to larger MW (FeFET Comparison) not reaching saturation current
- More Subloop Behaviour → Lower nonlinearity coefficient



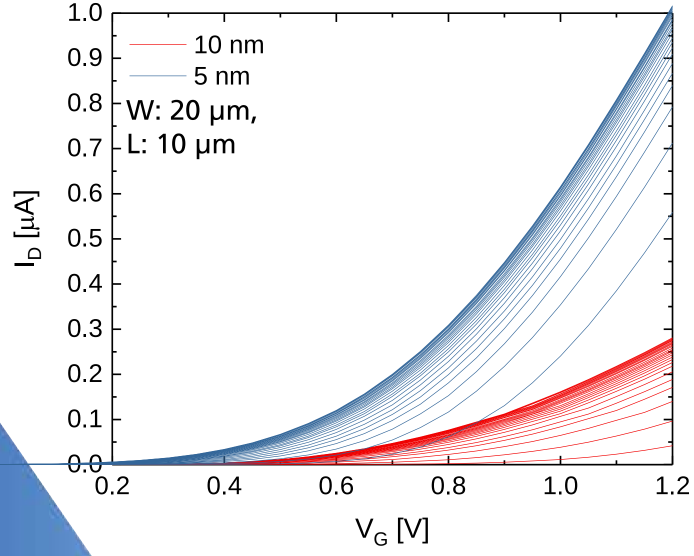


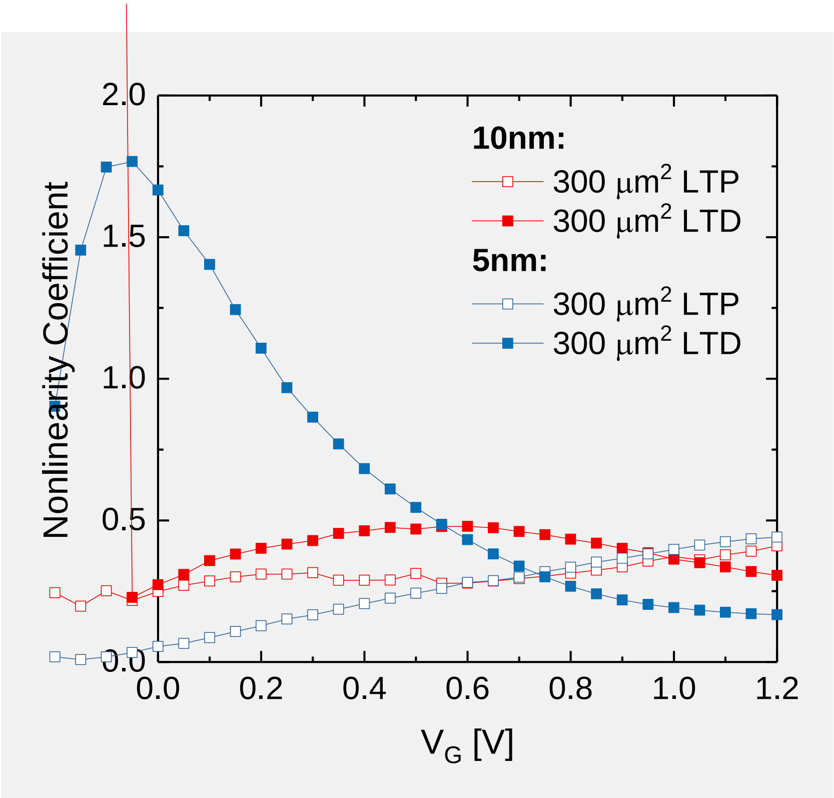


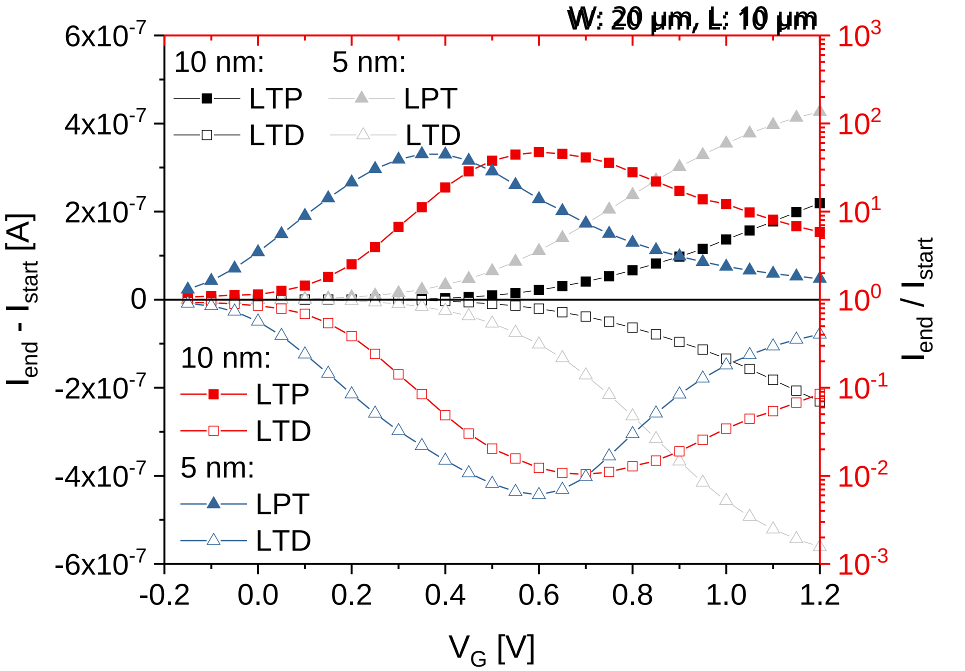
FeFET thickness influence



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







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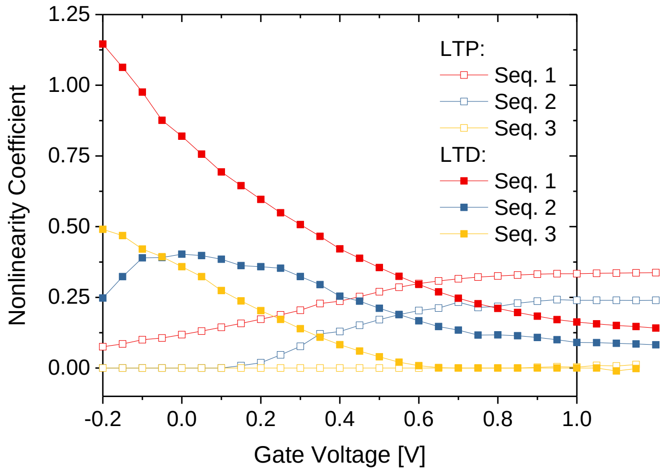
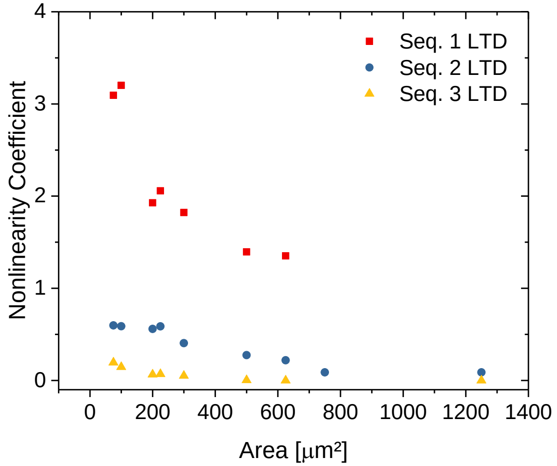
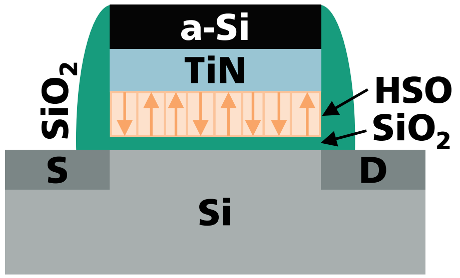
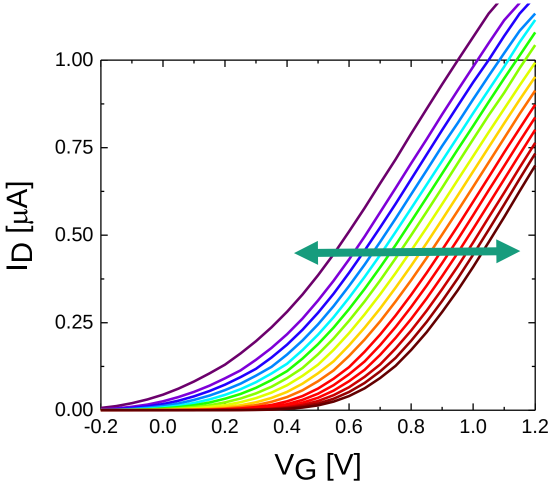
Conclusion & Outlook

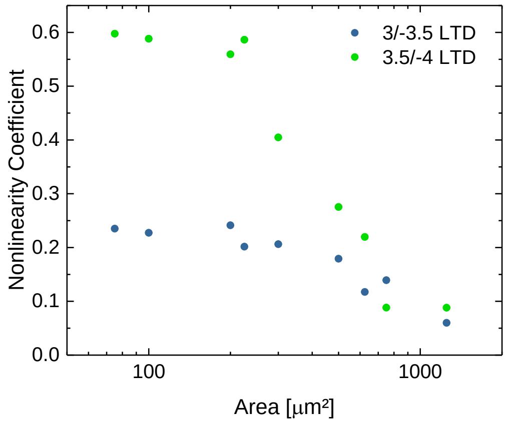
- Nonlinearity and variance can be tuned by signal shape and gate voltage
- Trade-off between variance and nonlinearity
- Scaling of area without strong increase in nonlinearity possible for sequence 2 and 3











Acknowledgements

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TEMPO

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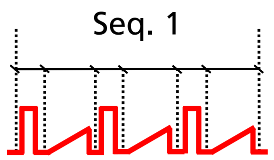
ECSEL Joint Undertaking

Bundesministerium für Bildung und Forschung

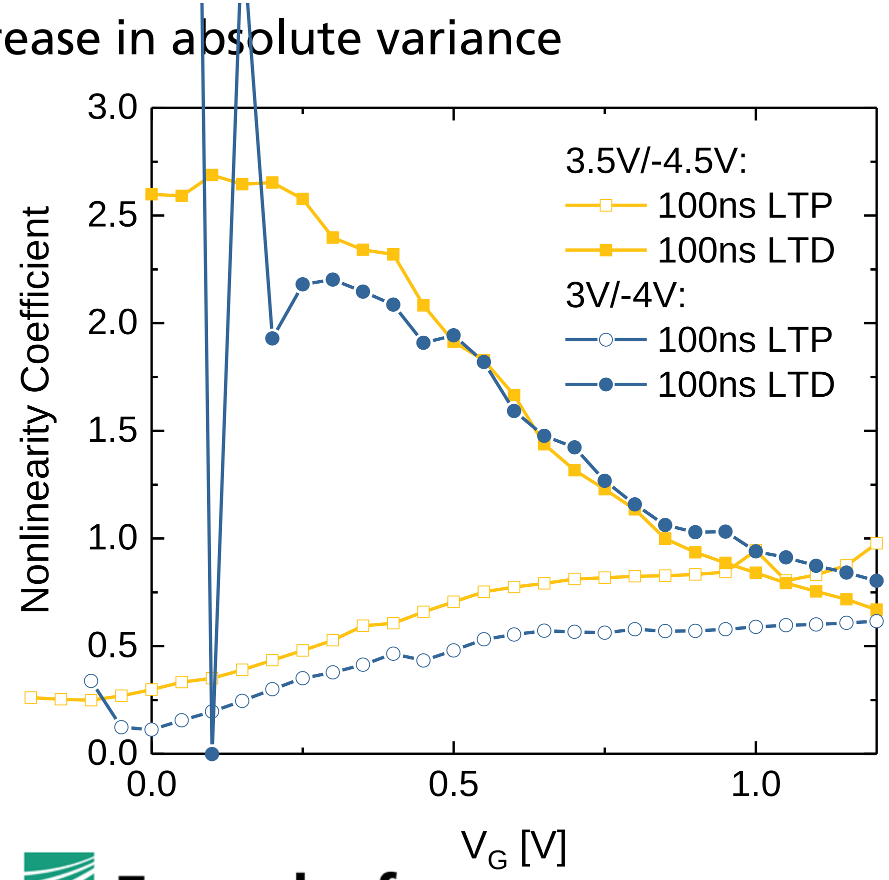
Freistaat SACHSEN

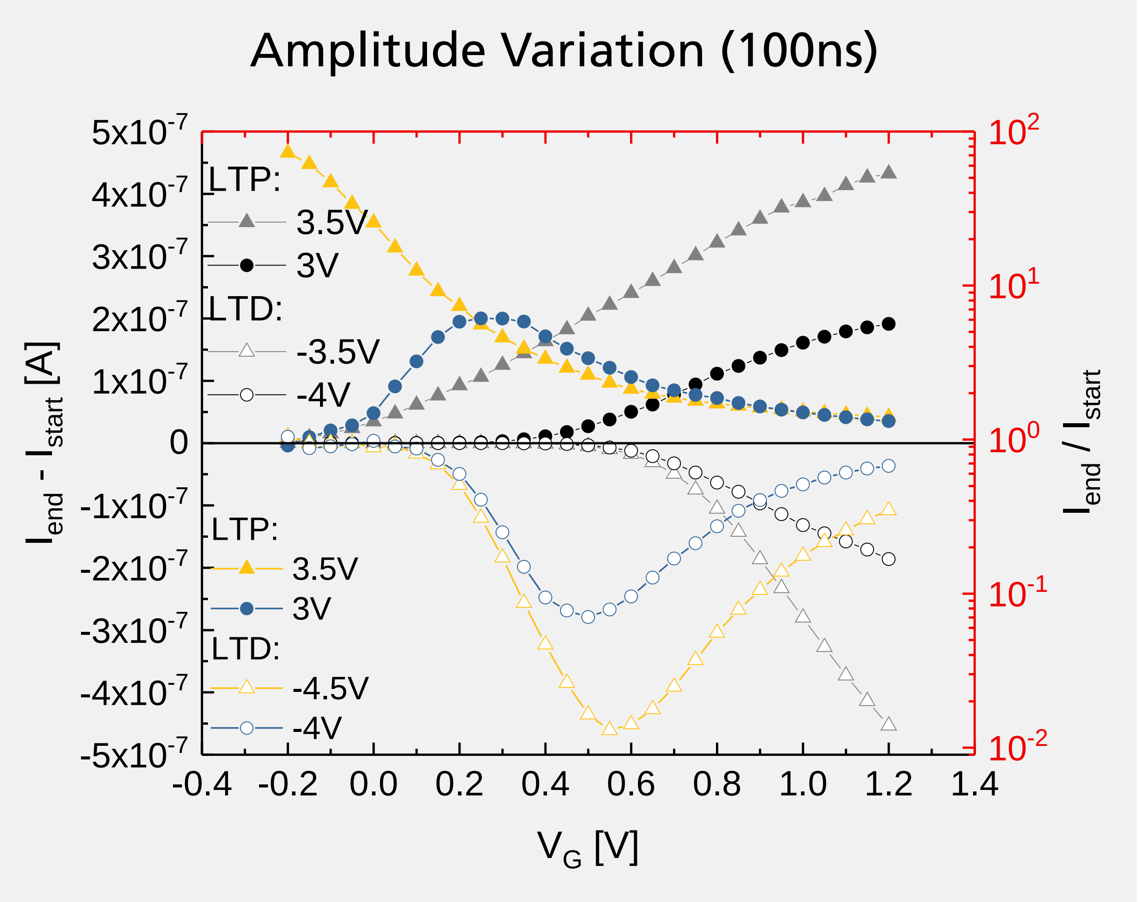
Sequence 1: Pulse Amplitude



Amplitude reduction:

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





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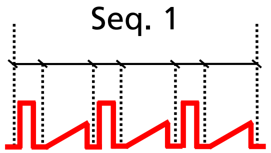
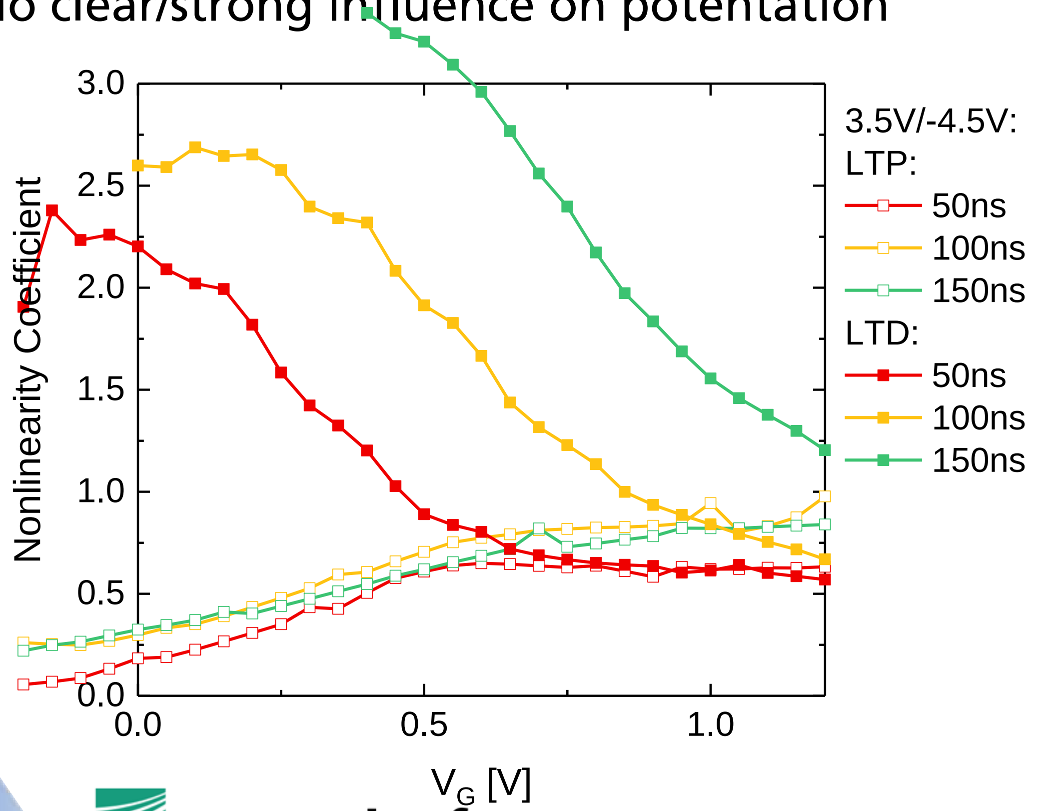
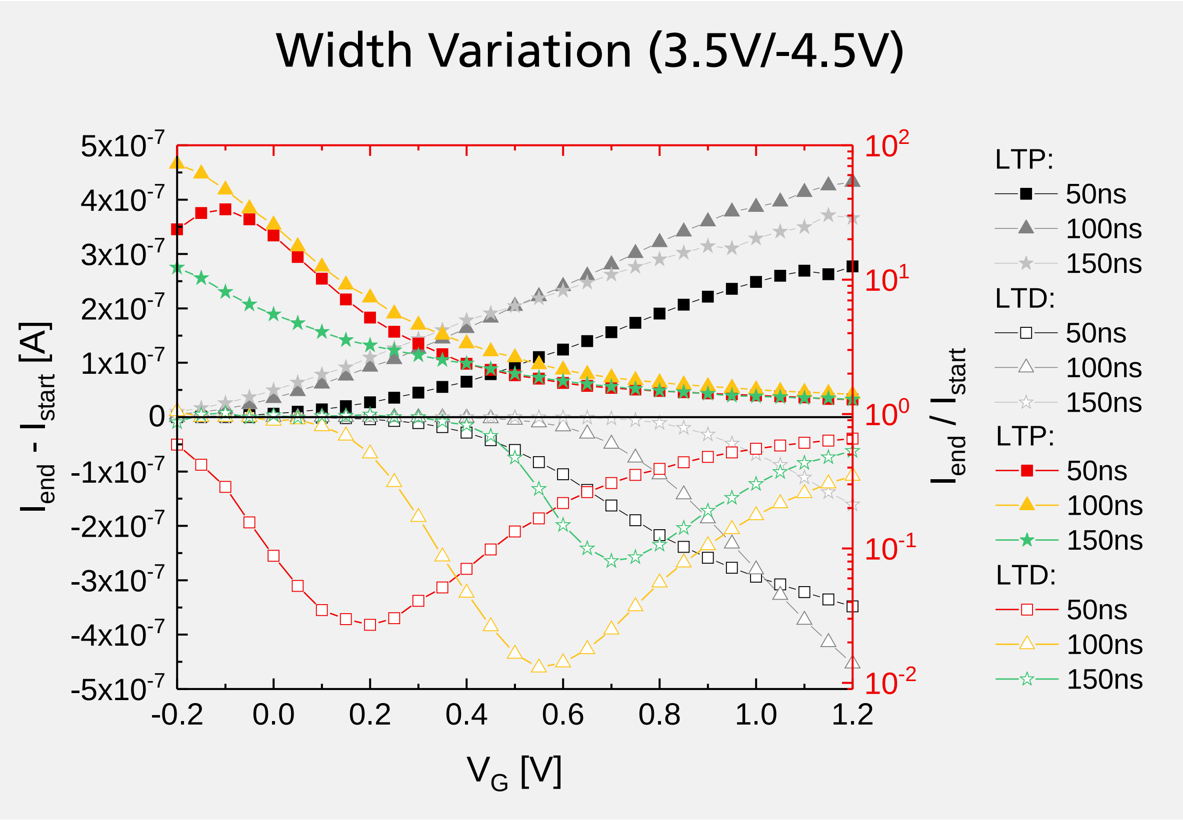


Sequence 1: Pulse Width

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





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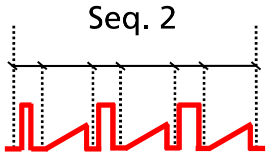
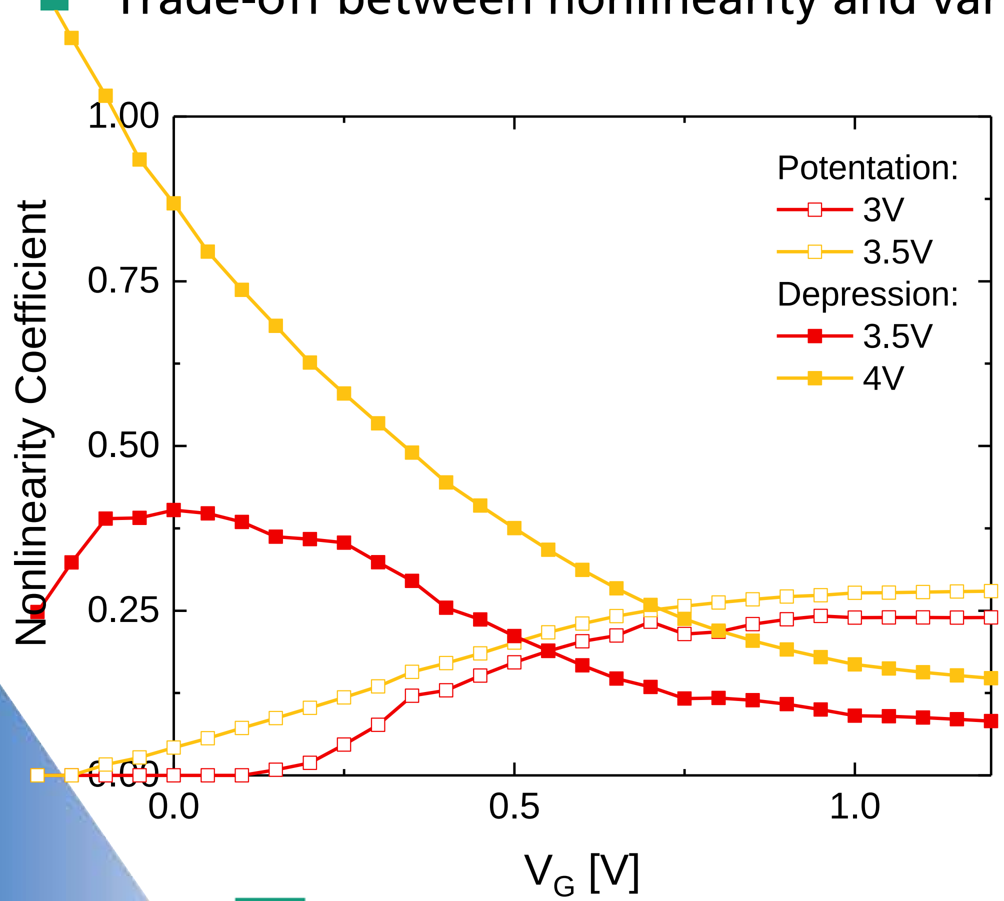
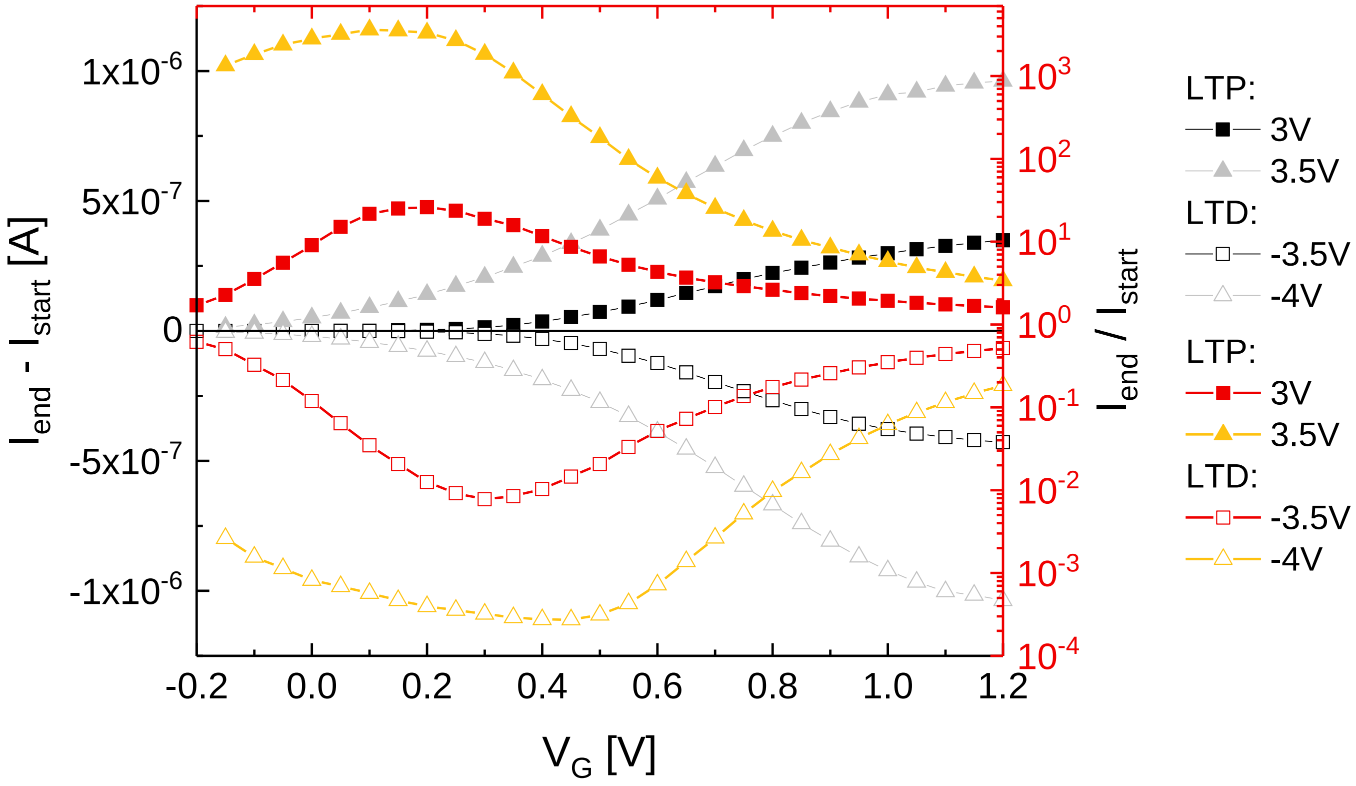
Sequence 2: Pulse Amplitude



- Trade-off between nonlinearity and variance





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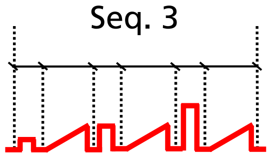
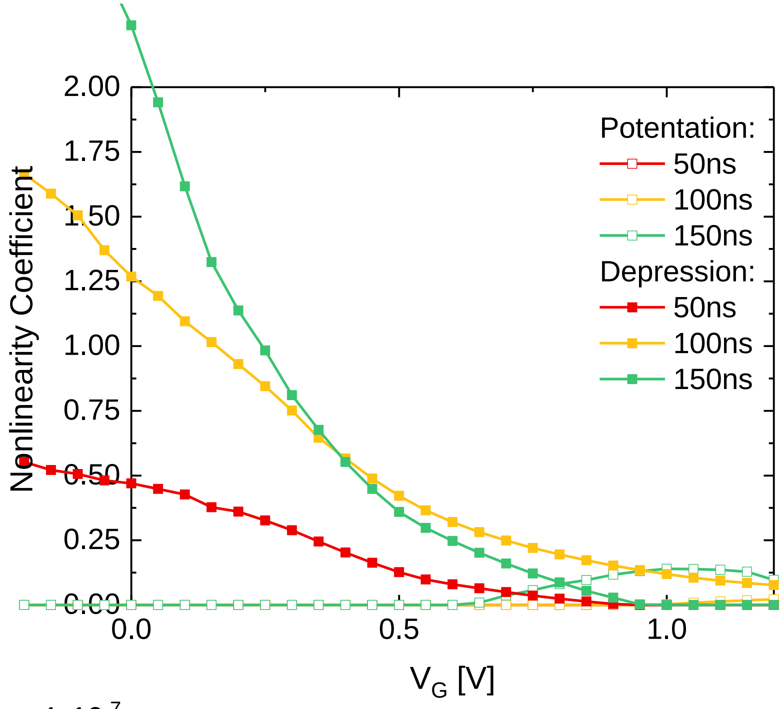
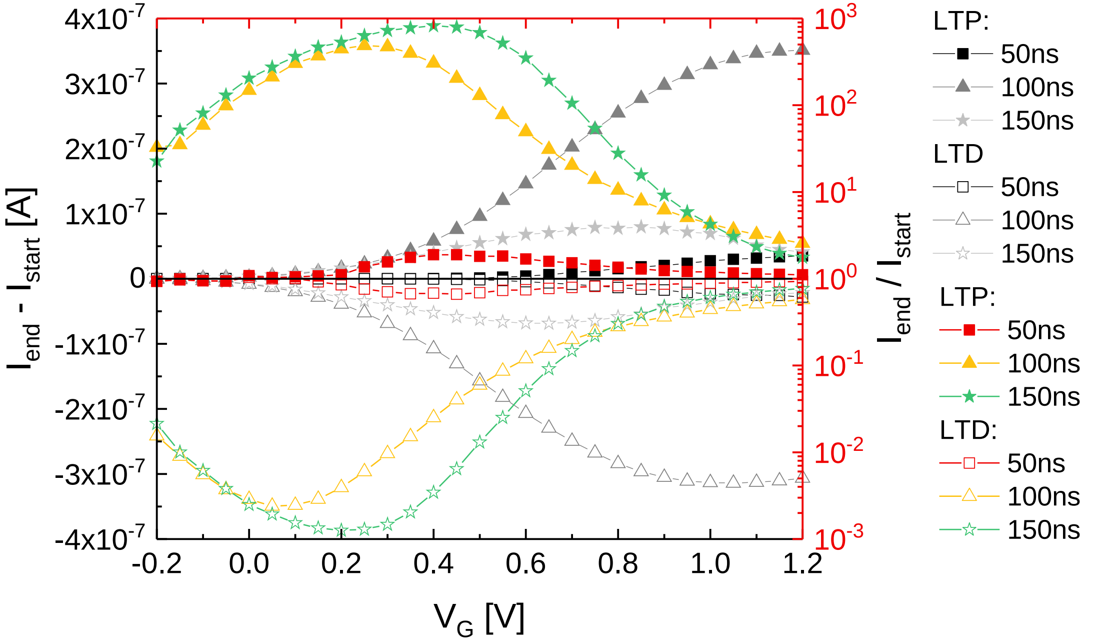
Sequence 3: Pulse Width



- Longer pulses increase slope of nonlinearity
- Absolute variance reaches maximum for 100ns

- Variance improvements with higher number of pulses





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