U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

Advanced Sensors and Instrumentation

Gallium Nitride-based 100-Mrad Electronics Technology for Advanced Nuclear Reactor Wireless Communications

Advanced Sensors and Instrumentation (ASI) Annual Program Webinar

October 24 – 27, 2022

PI: F. Kyle Reed, PhD

Oak Ridge National Lab

Project Overview

Research Purpose and Scope:

- Electronics technologies available for present day, in-service nuclear reactor sensing and communications are unsuitable due to high radiation and high temperature environments
- This project will investigate and demonstrate the suitability of gallium nitride (GaN) HEMT-based electronics for reactor sensor interfacing and wireless communications
- Validation of custom designs will be performed in both high temperature and high radiation environments
- Successful completion will advance the state-of-the-art in harsh environment electronics technologies for present and future advanced reactor applications

Participants:

Oak Ridge National Laboratory

- Kyle Reed (PI)
- Nance Ericson
- Dianne Bull Ezell
- Brett Witherspoon
- Lloyd Clonts

The Ohio State University

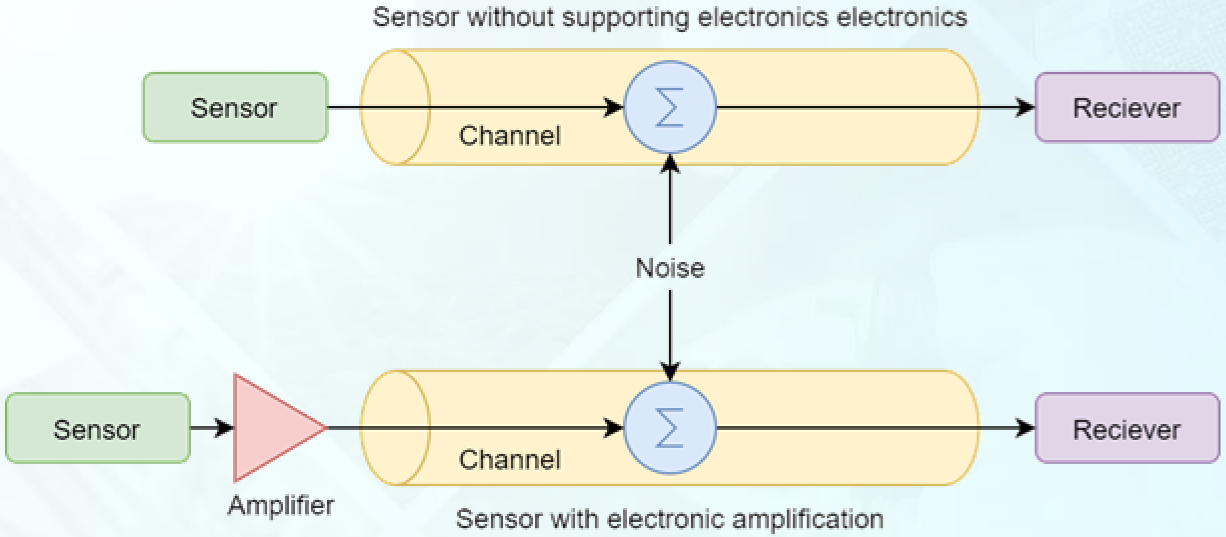
- Siddharth Rajan
- Raymond Cao
- Chandan Joishi
- Jack Lanza
- Hyunsoo Lee
- Adithya Balaji

Schedule:

- October 2021 – September 2024

Technology Impact: Why Radiation-Hardened Electronics?

- Placing sensors and associated electronics closer to a nuclear reactor core will improve reactor control and operation through increased signal accuracy, precision, and fidelity resulting in safer and more efficient energy production
- Electronics placed closer to sensors can multiplex and/or processes signals, reduce bandwidth for transmission, and reduce cabling and penetration requirements lowering costs and increasing infrastructural integrity



$$SNR = \frac{S}{N_{CH}}$$

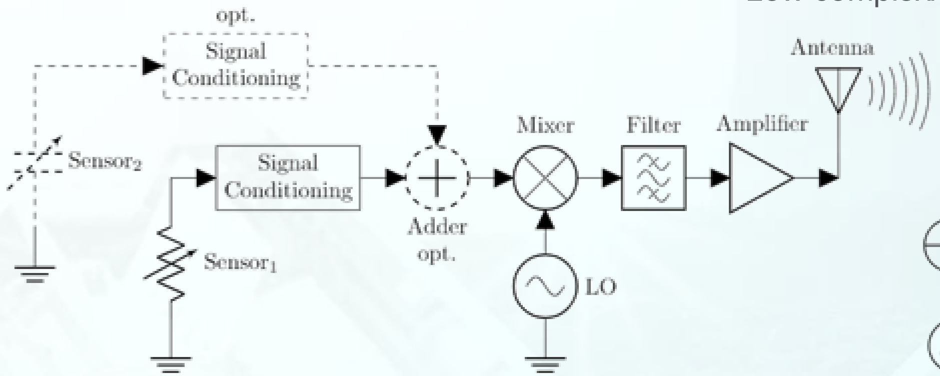
$$SNR = \frac{A \cdot S}{N_{CH} + N_A}$$

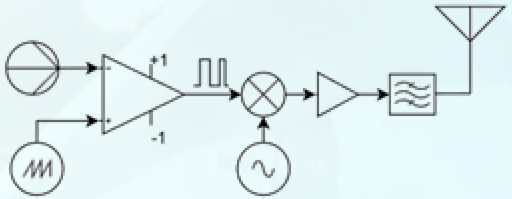
Technology Overview

Investigate and demonstrate the suitability of gallium nitride (GaN) HEMT-based electronics for reactor sensor interfacing and wireless communications.

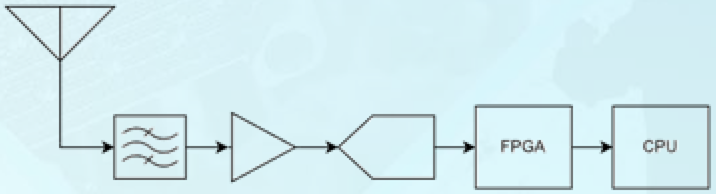
- Designing low complexity, cost effective, and radiation robust sensor signal conditioning and wireless transmission circuitry will increase safety and reliability while reducing maintenance costs associated with nuclear reactors, spent fuel casks, and emergency robotics
- Complex algorithms can be performed in a low-radiation environment

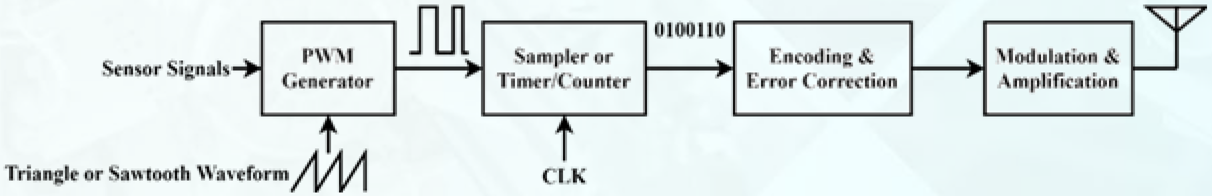
Low complexity transmitter examples



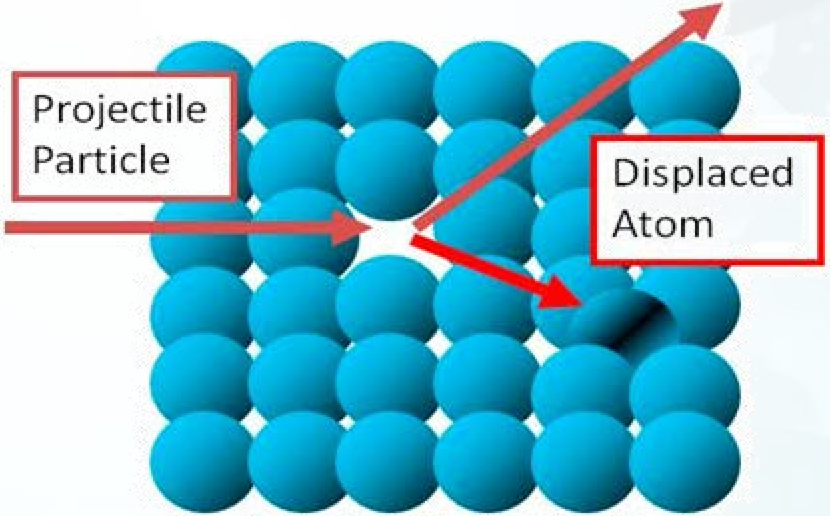


High complexity receiver

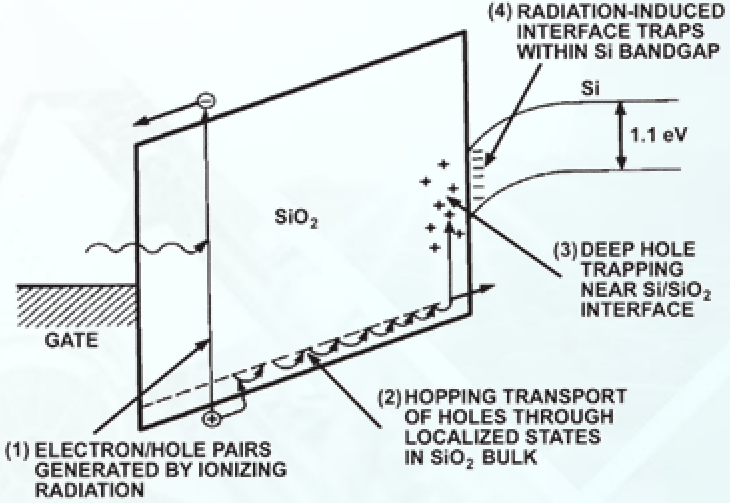




Radiation Effects on Semiconductor Devices



https://wpo-altertechnology.com/displacement-damage-testing/



A. Dawiec, Development of an ultra-fast X-ray camera using hybrid pixel detectors, HumanComputer Interaction [cs.HC], Universite de la Mediterranee — Aix-Marseille II, Marseille France (2011)

- Neutrons
  - Neutrons will transfer energy to interstitial atoms displacing atoms which may recombine with dopant or impure atoms producing stable defects
  - Minority carrier removal and increased material resistivity are associated with neutron displacement damage
- Ionizing Radiation
  - Compton effect and pair creation from high energy photons create ions in the incident materials
  - Charges are trapped in electrical insulators that generate electric fields and induce currents
  - Dose rates contribute to single event errors such as single event upsets or latch ups

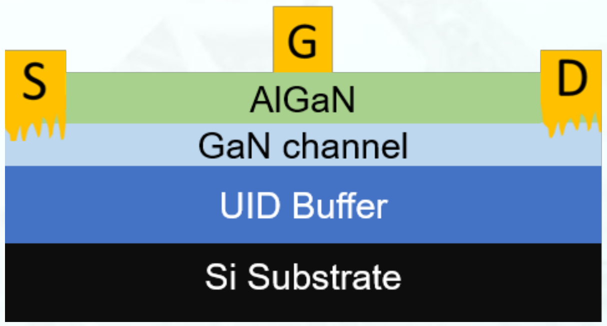
Si-Based Electronics Components Radiation Limits

	Neutron Displacement Damage [1]		**Total Ionization Dose (TID) Damage** [2]	
	Max Fluence (n/cm^2)	Displacement effect	TID (rad)	TID effect
Diodes/ Photodiodes	10^{13}-10^{15}	↑ leakage current; ↑ forward voltage threshold	10^{6}-10^{8}	↑ photocurrents
LEDs	10^{12}-10^{14}	↓ light intensity	10^{7}-10^{8}	0.25 dB attenuation
BJTs	10^{13}	Current gain degradation	10^{5}-10^{7}	Current gain degradation; ↑ leakage current
JFETs	10^{14}	↑ channel resistivity; ↓ carrier mobilities	$>10^{8}$	Minimal effects
SiC JFETs	10^{16}	↑ channel resistivity; ↓ carrier mobilities	$>10^{8}$	Minimal effects
MOSFETs	10^{15}	↑ channel resistivity; ↓ carrier mobilities	10^{6}	↑ threshold voltage; ↑ leakage current
CMOS	10^{15}	↑ channel resistivity; ↓ carrier mobilities	10^{8}	variation in threshold voltage; variations in leakage current

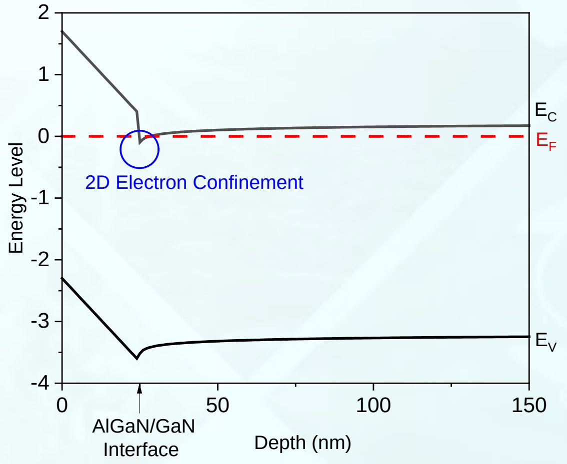
[1] Neamen, Donald A. Semiconductor physics and devices: basic principles. New York, NY: McGraw-Hill,, 2012.
[2] H. Spieler, "Introduction to radiation-resistant semiconductor devices and circuits." AIP Conference Proceedings. Vol. 390. No. 1. American Institute of Physics, 1997.

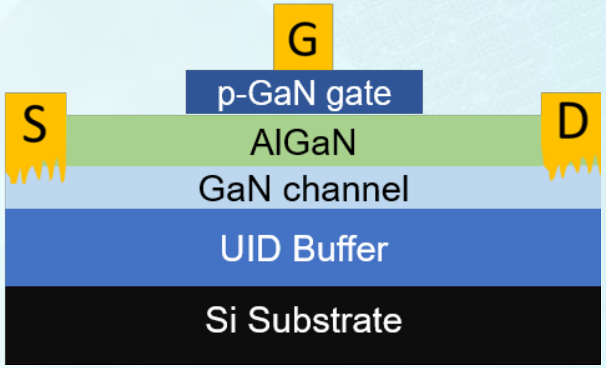
Why GaN?

- High bonding in binary and ternary nitrides makes GaN devices intrinsically resistant to displacements
- Enhancement-mode (E-mode) and depletion-mode (D-mode) device fabrication and operation is possible without requiring gate insulation for the field effect devices
- The 2D electron gas (2DEG) allows for channel charges as high as 3×10^{13} cm^{-2} without introducing dopants, which allows for high channel mobilities by reducing impurities
- GaN HEMTs have been shown to withstand 600 Mrad ionizing dose (neutron limits are under investigation)

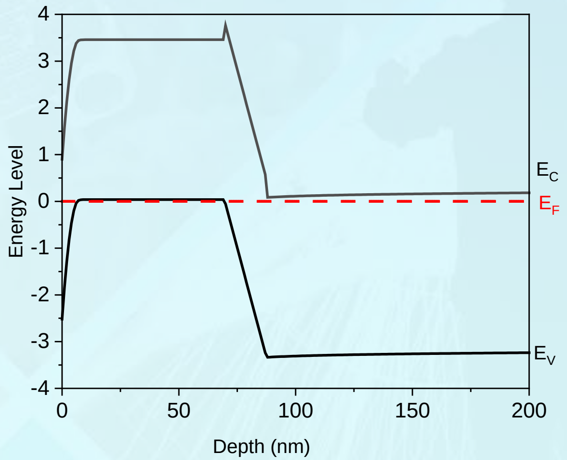


GaN HEMT Depletion Mode Device



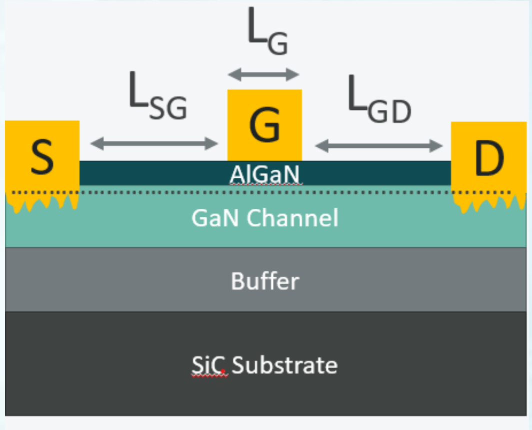


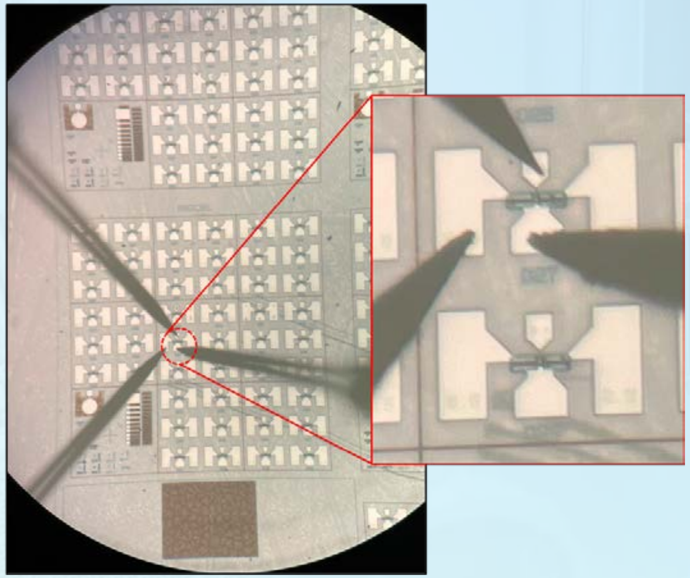
GaN HEMT Enhancement Mode Device



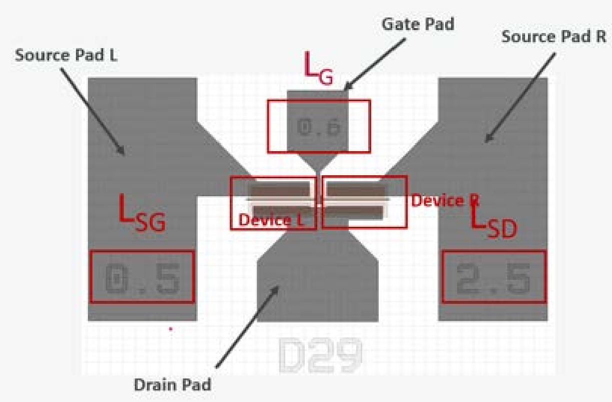
Early GaN HEMT Fabrication

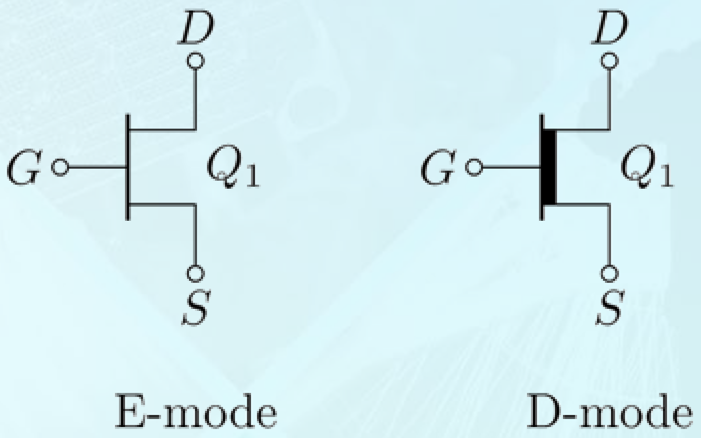
- AlGaN/GaN HEMTs with 0.7 μm gate length were fabricated at OSU and delivered to ORNL
- Devices were fabricated on commercially obtained AlGaN/GaN epitaxial layers
- Devices show good on-current (> 900 mA/mm), f_T/f_{MAX} (~19 GHz/40 GHz)





Layer #	Name
2	MESA isolation
3	Ohmic contact (Ti/Al/Ni/Au)
4	P-GaN recess pattern
5	M1 layer
6	Bondpad window

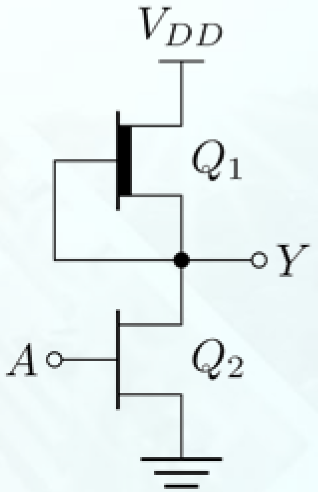




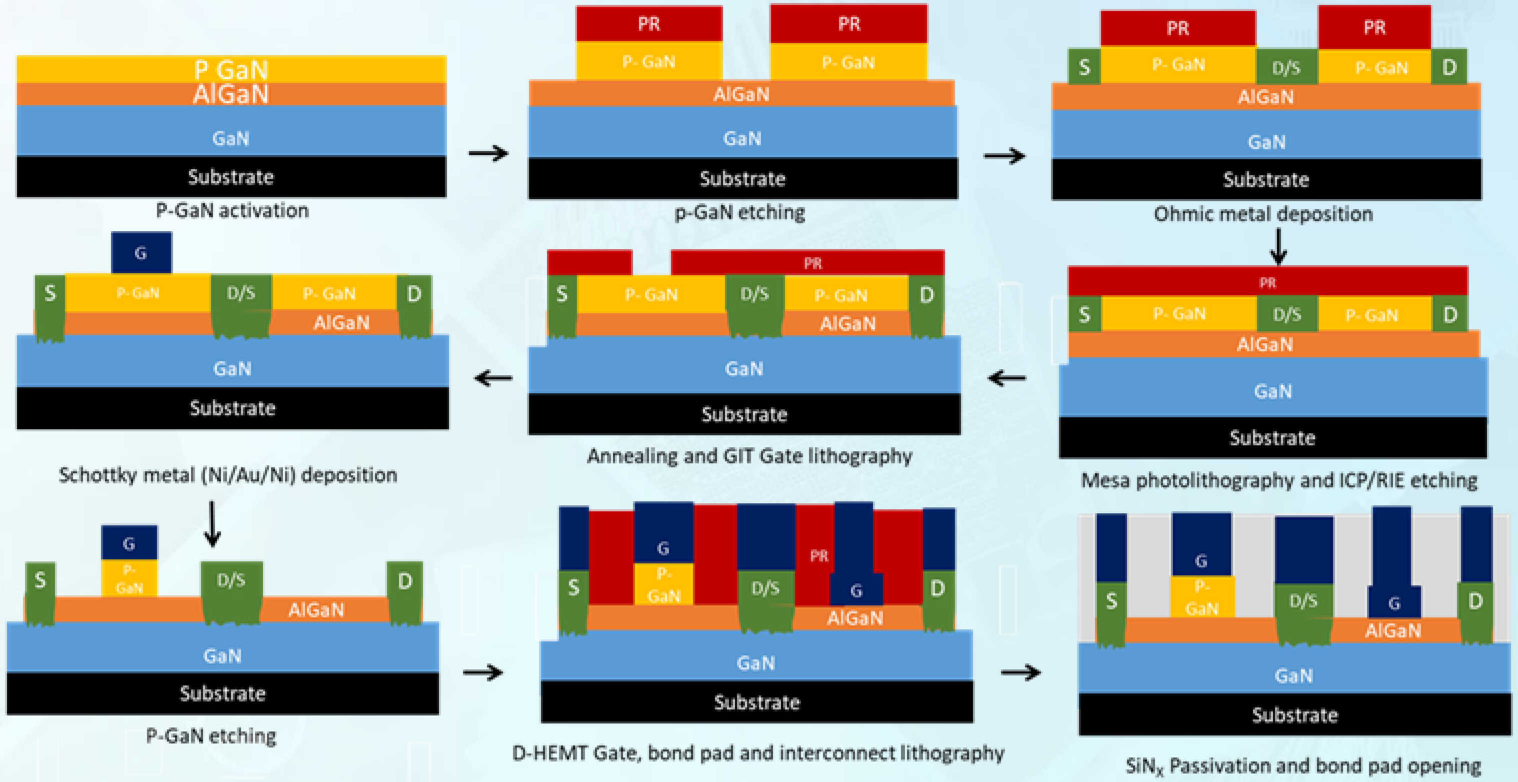
GaN HEMT Fabrication Process

- Process flow for monolithic enhancement-depletion mode circuits is being developed on commercially obtained epitaxial wafers (p-GaN/AlGaN/GaN/sapphire)
- Process parameter optimization for etch, contacts is underway
- Epitaxial wafers from vendors are being qualified for device fabrication

Logic Inverter With Enhancement Mode Pull-down and Depletion Mode Pullup HEMTs



OSU GaN Inverter Fabrication Process



Empirically Derived Compact GaN Device Models (Verilog-A)

Verilog-A Model Derived by Fitting Measured Data

Fitting Function (Levenberg-Marquardt algorithm)

$$\boxed{I_D = K_1 \tanh(K_2 V_{DS})(1+K_3 V_{DS})}$$

$K_1(V_{GS})$ = 4^{th} order polynomial (v_{sat}, g_m)

$$= M_1\, V_{GS}^4 + M_2 V_{GS}^3 + M_3 V_{GS}^2 + M_4 V_{GS} + M_5$$

$K_2(V_{GS})$ = 5^{th} order polynomial (R_{on})

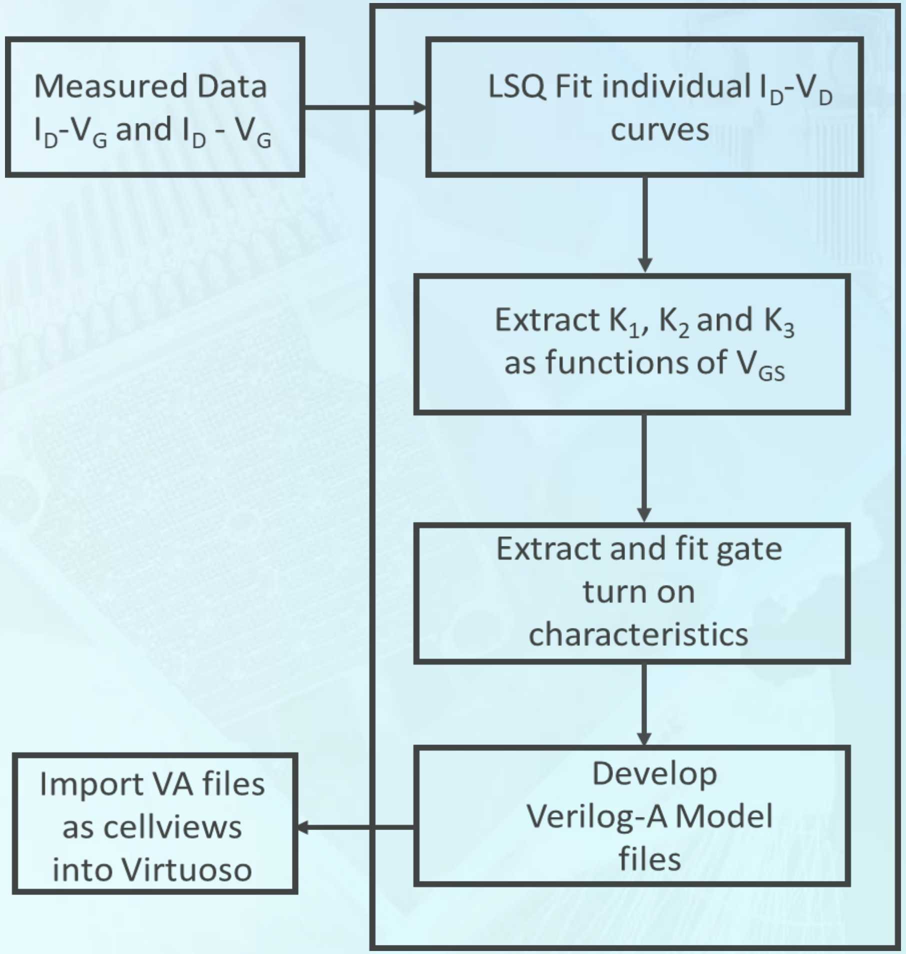
$$= P_1\, V_{GS}^5 + P_2 V_{GS}^4 + P_3 V_{GS}^3 + P_4 V_{GS}^2 + P_5 V_{GS} + P_6$$

$K_3(V_{GS})$ = 4^{th} order polynomial (g_o in saturation)

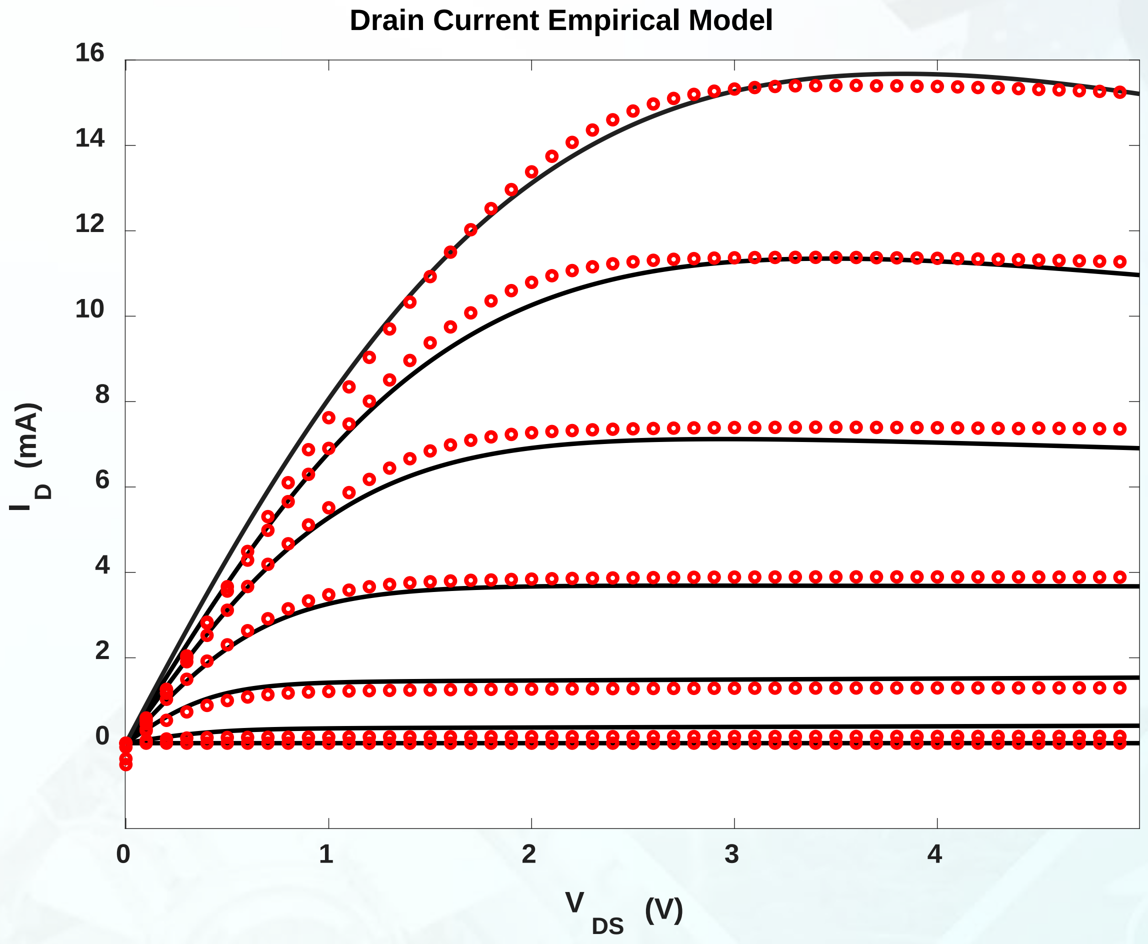
$$= A_1\, V_{GS}^4 + A_2 V_{GS}^3 + A_3 V_{GS}^2 + A_4 V_{GS} + A_5$$

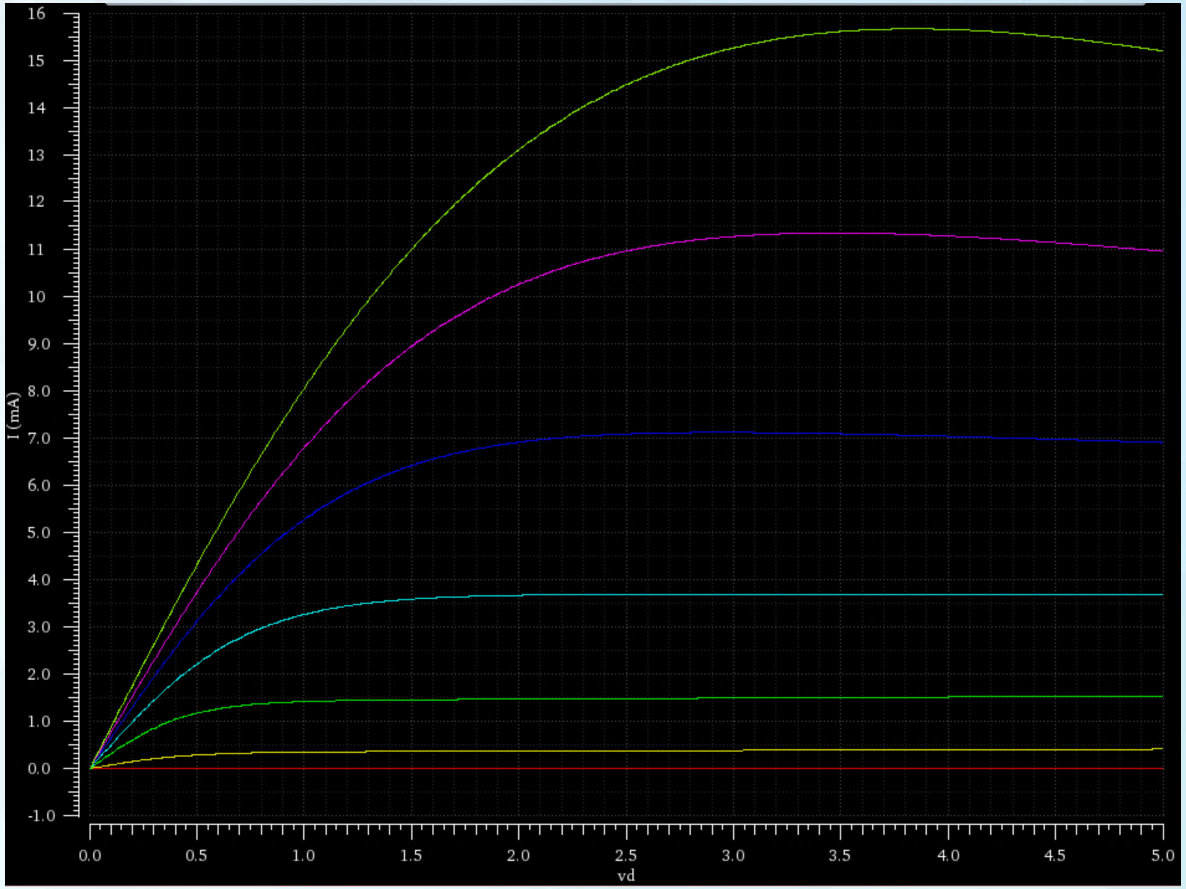
The model converges for V_{GS} < 2.5 V

Model Development Process Flow



Empirically Derived Compact GaN Device Models (Verilog-A)





W = 104 µm, L_G = 4 µm, L_{SG} = 2 µm, L_{GD} = 2 µm

Binary Modulation Schemes

On-Off Keying

- Simple implementation
- Narrowband method
- Binary values represented presence of carrier f_c

$$s(t) = \begin{cases} \cos 2\pi f_c + \theta \\ 0 \end{cases}$$

Frequency-Shift Keying

- Increasing complexity
- Robust narrowband method
- Constant envelope
- Binary values represented by differing frequencies f_0 and f_1

$$s(t) = \begin{cases} \cos 2\pi f_0 + \theta_0 \\ \cos 2\pi f_1 + \theta_1 \end{cases}$$

Chirp Keying

- Significant complexity
- Spread spectrum method
- Constant envelope
- Values represented by increasing or decreasing instantaneous frequency

$$s(t) = \begin{cases} e^{-i2\pi t(\frac{f_{max}-f_{min}}{T}+f_{min})} \\ e^{-i2\pi t(\frac{f_{min}-f_{max}}{T}+f_{max})} \end{cases}$$

Encoding Schemes

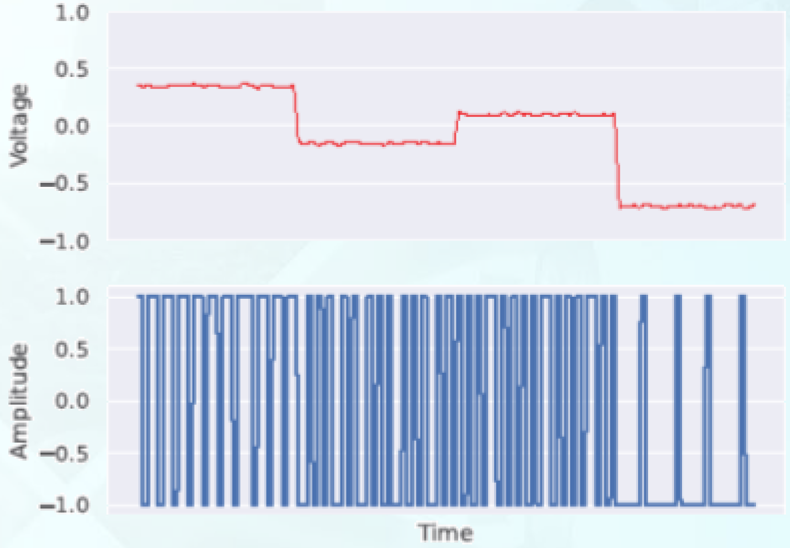
Pulse-Width Encoding

- Simple implementation
- Analog values encoded in duty cycle of rectangular waveform
- A form of temporal encoding

$$s(t) = \begin{cases} s_0(t) & 0 \leq t < DT \\ s_1(t) & DT \leq t < T \end{cases}$$

Pulse-Density Encoding

- Increasing complexity
- Leverages delta-sigma modulation to encode analog values
- A form of rate encoding

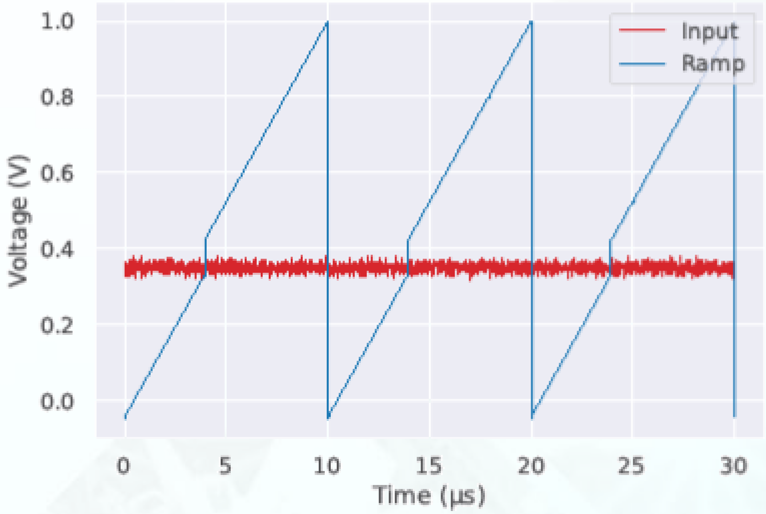


Binary Encoding

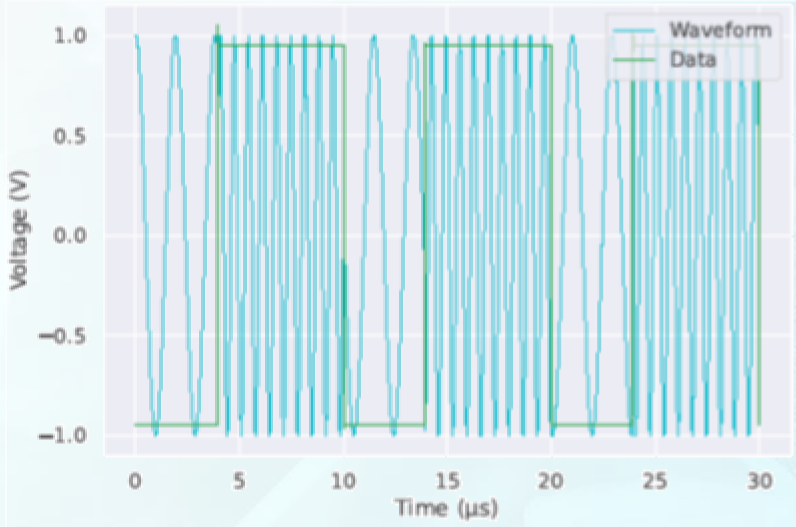
- Significant complexity
- Traditional binary analog-to-digital converter
- Enables integration with fully digital systems and digital error-correcting codes

Frequency-Shift Keying with Pulse Width Encoding Simulation

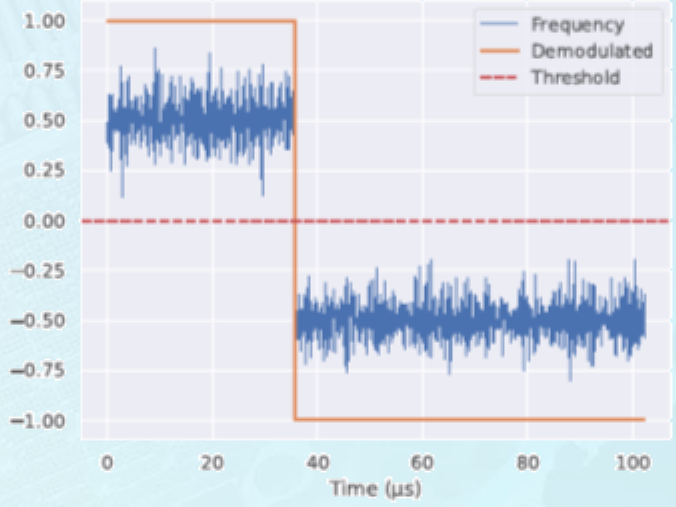
- Continuous-time simulations of transmitter and discrete-time simulation of receiver designs
- Noise introduced to sensor measurements and transmitted waveform



Noisy sensor input (red) compared to a ramp (blue) to determine the logic level output of the transmitted waveform

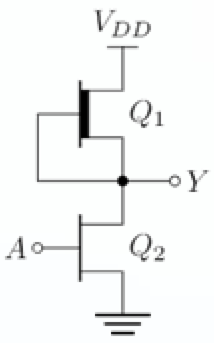


Frequency shift key of the binary data (green) and the transmitted sinusoidal waveforms of two frequencies representing the high and low logic level

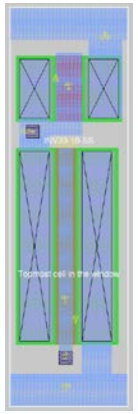


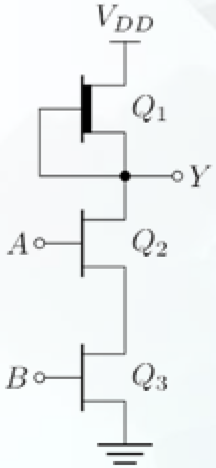
Demodulation of the FSK signal with frequency plus noise (blue) shifted depending on the logic high or low state, detected by a threshold (red-dashed), and demodulation estimate (orange)

Depletion-Load Logic Circuits and Layouts (Magic)

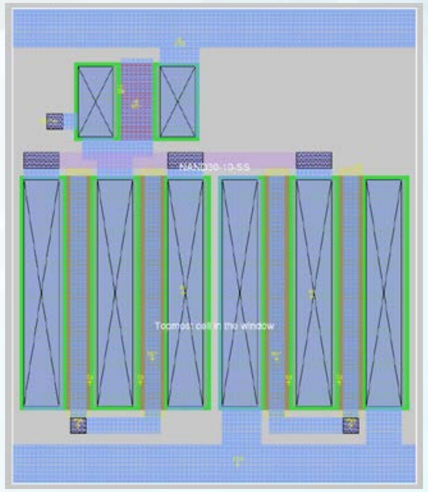


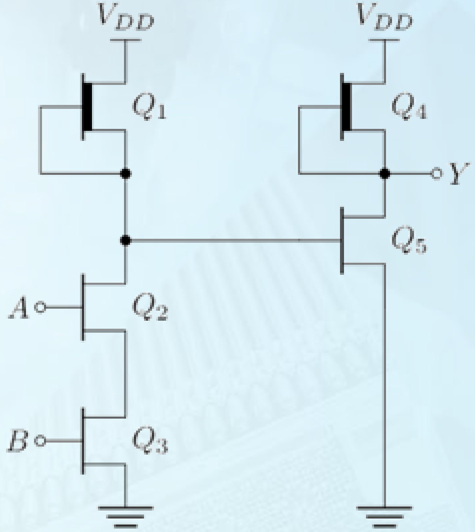
NOT



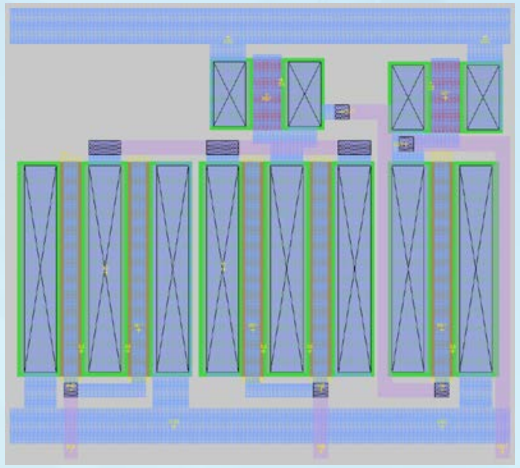


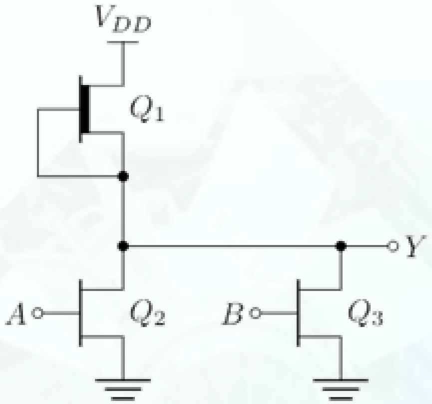
NAND



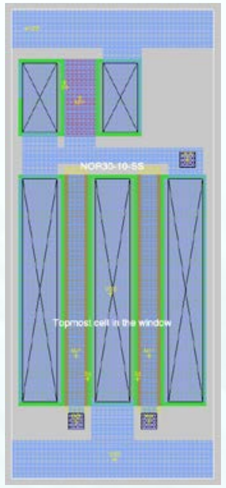


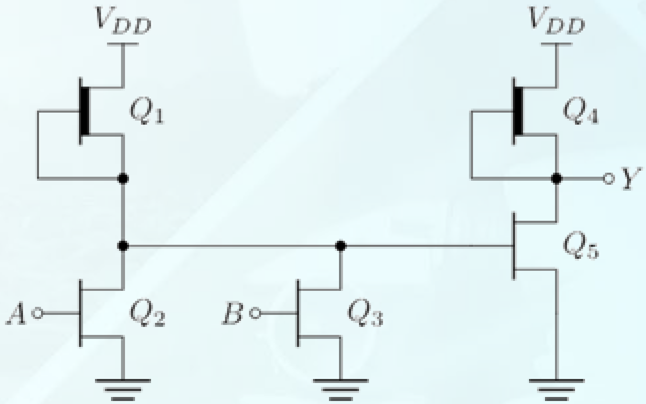
AND



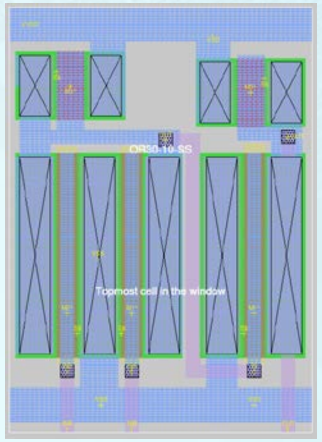


NOR





OR



NOT Truth Table

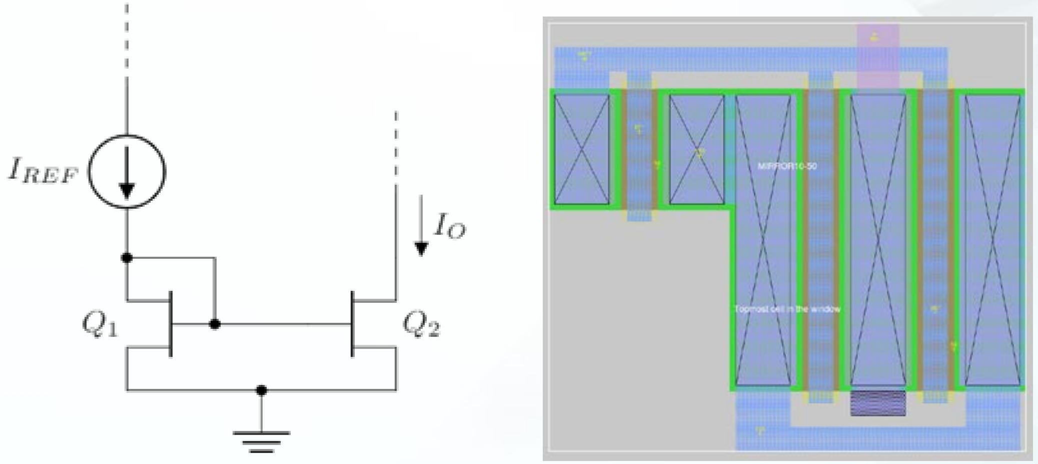
Input	Output
A	Y
0	1
1	0

2-Input Logic Truth Table

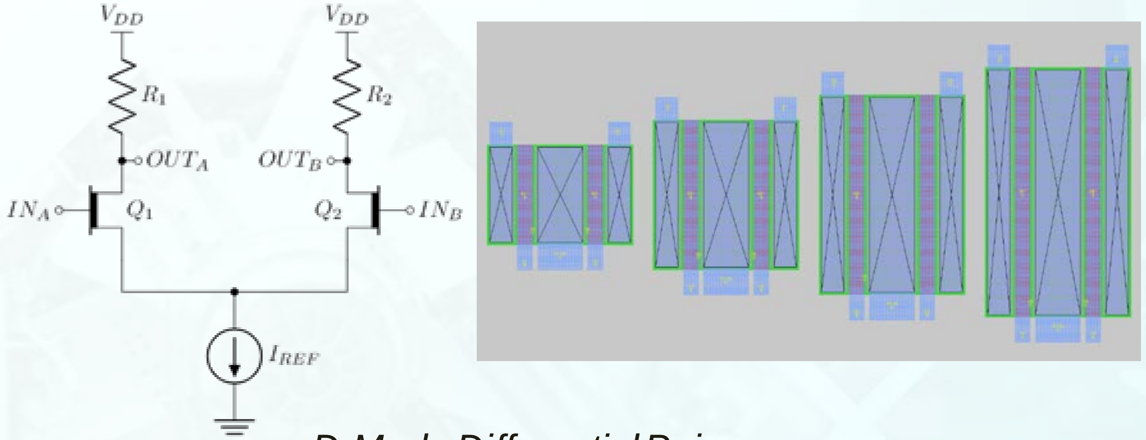
Input		Output (Y)			
A	B	NAND	AND	NOR	OR
0	0	1	0	1	0
0	1	1	0	0	1
1	0	1	0	0	1
1	1	0	1	0	1

Note: All D-mode devices have W/L=10 µm / 4 µm; All E-mode devices have W/L = 30 µm / 3 µm

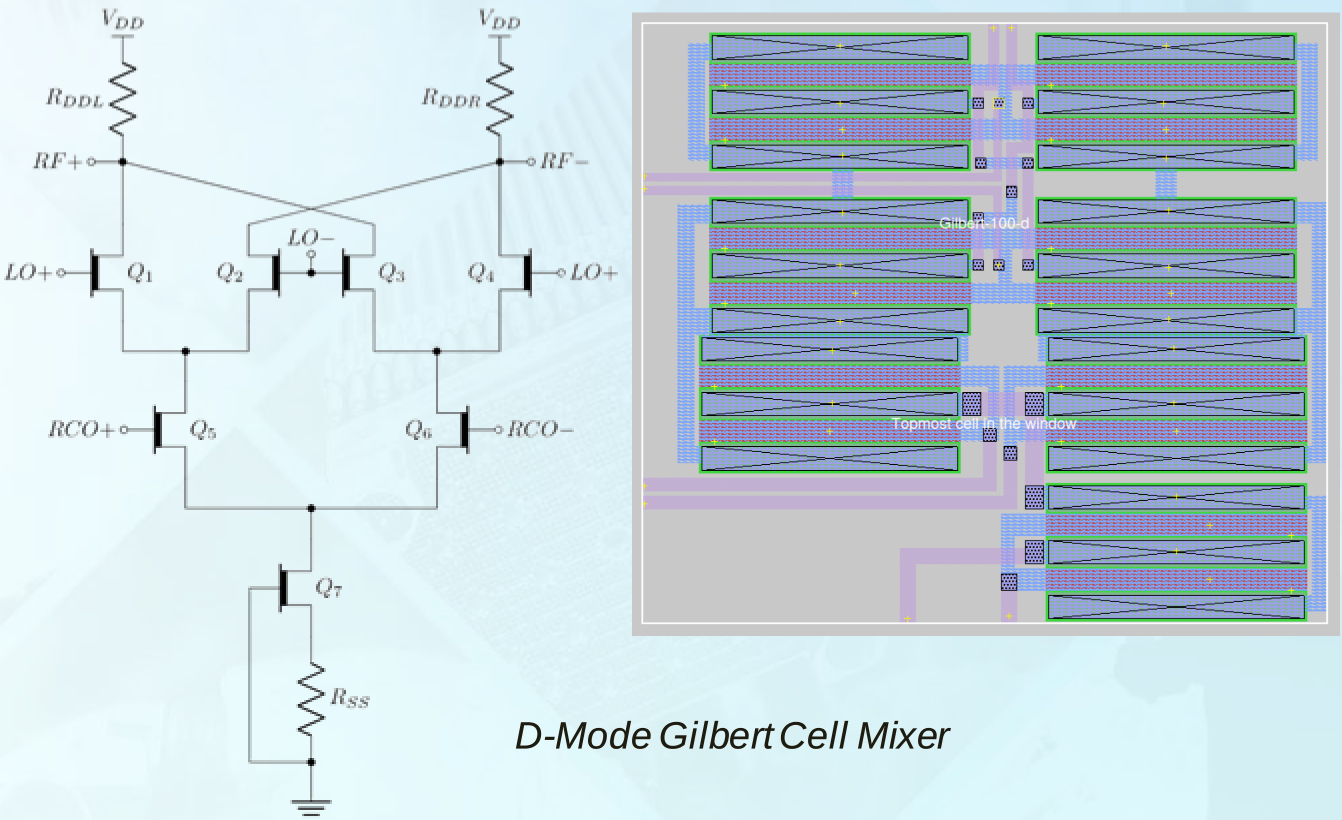
Select Analog Circuits and Layouts (Magic)



E-Mode Current Mirror



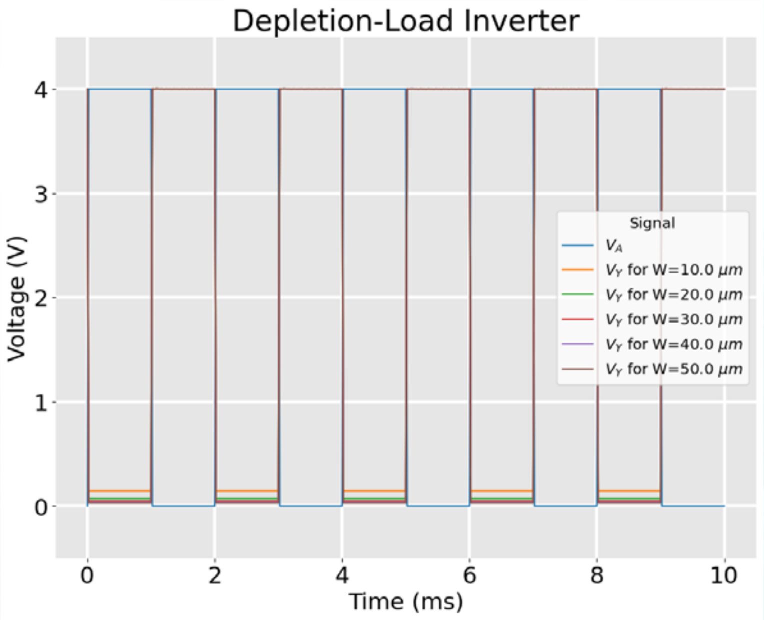
D-Mode Differential Pairs

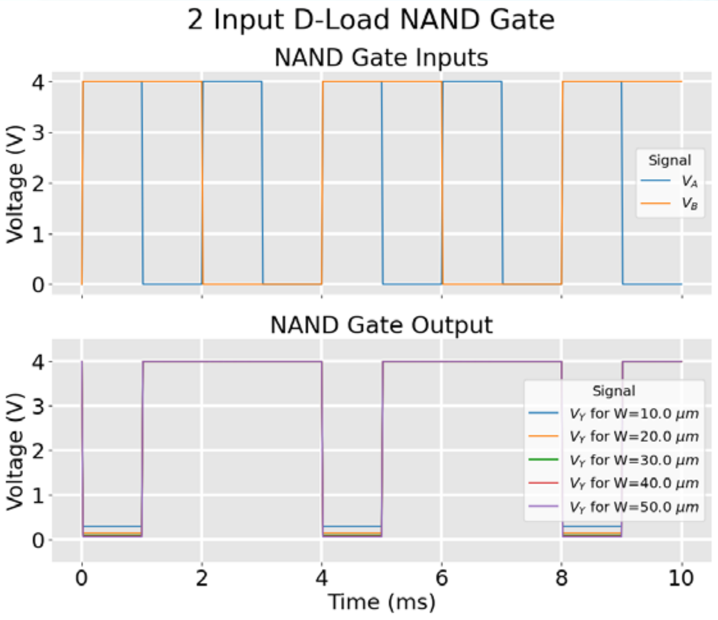


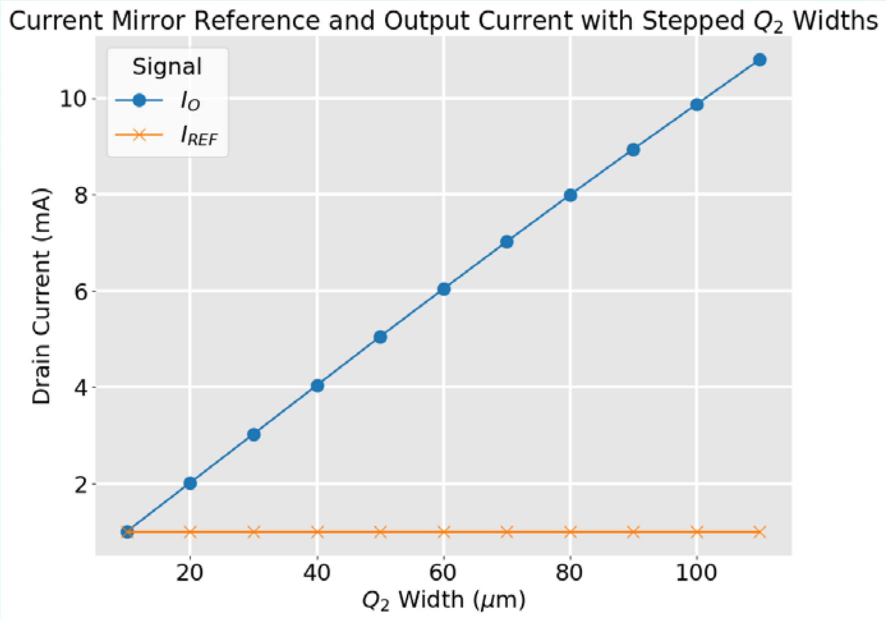
D-Mode Gilbert Cell Mixer

Selected Circuit Simulations

- Simulations of the GaN HEMT-based circuits were performed in QucsStudio (http://qucsstudio.de/)
- Models do not converge with voltages beyond 4 V
- Digital devices require D-mode devices to have W/L ≥ 3 compared to their E-mode input device
- The simulated oscillators (RC-phase, Colpitts, and ring) resonate near their theoretical resonance
- The simulated current mirror output current scales linearly with ratioed widths and lengths $I_0 = \frac{W_2/L_2}{W_1/L_1} I_{ref}$





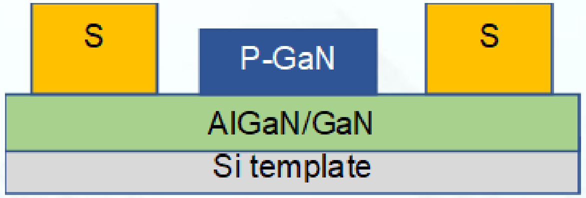


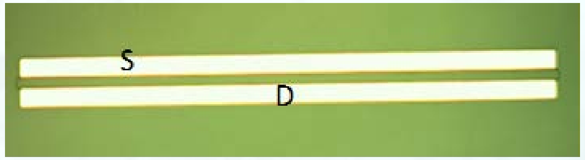
Assorted Analog and Digital Cells and Associated Device Sizes

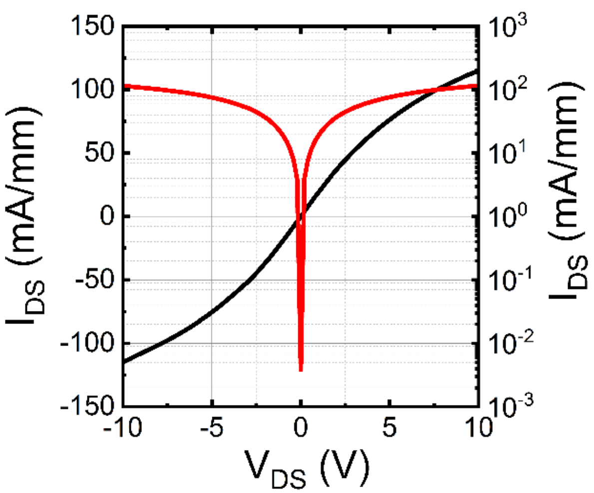
Cell	Description	Device sizes (W/L) D-mode (μm)	Device sizes (W/L) E-mode (μm)
NOT gate	Logic inverter	10/4	30/3
NAND gate	2-input NAND gate	10/4	30/3
AND gate	2-input AND gate	10/4	30/3
NOR gate	2-input NOR gate	10/4	30/3
OR gate	2-input OR gate	10/4	30/3
Ring Oscillator	5-stage logic inverter topology	10/4	30/3
D-mode differential pair	4 pairs		20/4, 30/4, 40/4, & 50/4
E-mode differential pair	4 pairs	20/3, 30/3, 40/3, & 50/3	
E-mode current mirror	5:1 ratio		10/4 : 50/4
D-mode Gilbert cell	Balanced mixer	50/4	
E-mode ELT	Single device with annular gate		30/3
Interdigitated E-mode ELT	4 interdigitated with annular gate		30/3

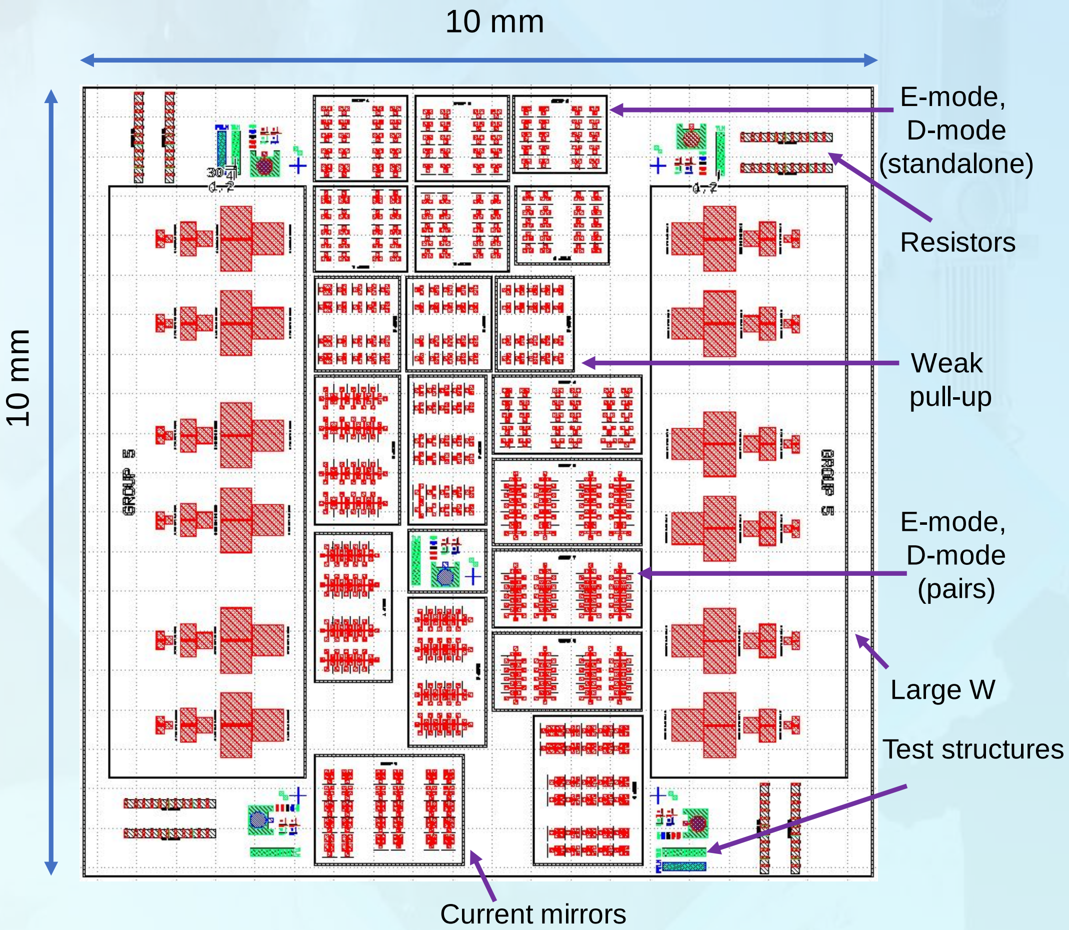
Recent GaN Device Fabrication

- A new GaN process run of devices (E-mode, D-mode, resistors, differential pairs, and current mirrors) has been successfully completed
- Devices are being evaluated presently
- Once devices are evaluated, the compact models will be updated to include any process variations









	MESA
	Ohmic
	p-GaN
	Schottky
	Pad Window

Concluding Remarks

- State-of-the-art silicon-based electronics are not suitable for high temperature radiation environments associated with nuclear reactors and spent fuel storage
- Wide bandgap GaN is a promising semiconductor material for these harsh conditions
- Test GaN E-mode and D-mode devices have been fabricated at OSU and tested
- Compact circuit models for OSU's GaN HEMT process have been developed
- Digital wireless communication protocols of different complexities have been investigated
- An assortment of analog and digital circuits have been simulated in QucsStudio, and their corresponding cell layouts have been designed in Magic

Looking ahead:

- Fabrication of new circuit cells (analog and digital) is underway at OSU
- Additional layers are being added to the OSU process (and layout/extraction tools)
- A GaN device irradiation is planned for January 2023 in the OSU research reactor
- Circuits of increasing complexity will be designed and validated in the OSU GaN process

Thank You

Kyle Reed
R&D Staff, Oak Ridge National Lab
reedfk@ornl.gov