Radiation Tolerant Wide Bandgap Microelectronics

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Outline

- Wide and ultrawide bandgap (WBG) semiconductors for radiation-tolerant applications
- Fin geometry field-effect transistors for increased robustness to radiation-induced damage
- β-Ga_2O_3 FinFET process development and device characteristics
- Conclusion & future work

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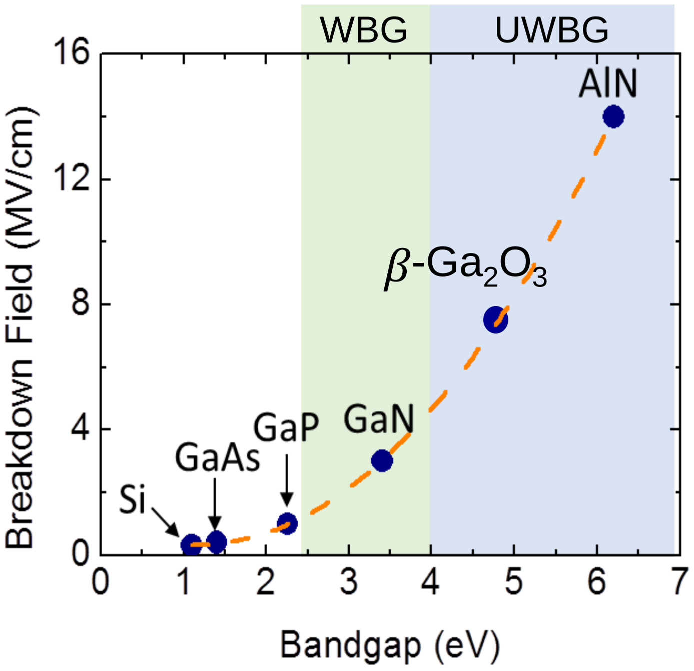
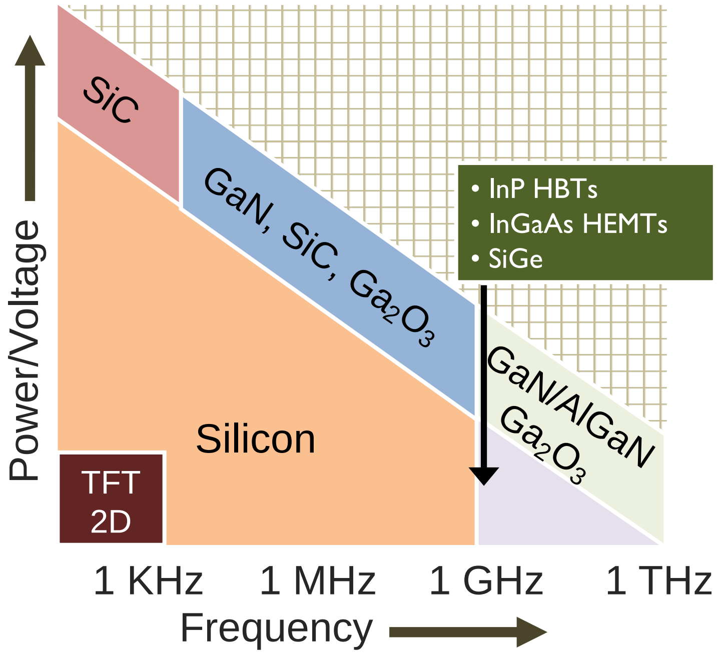
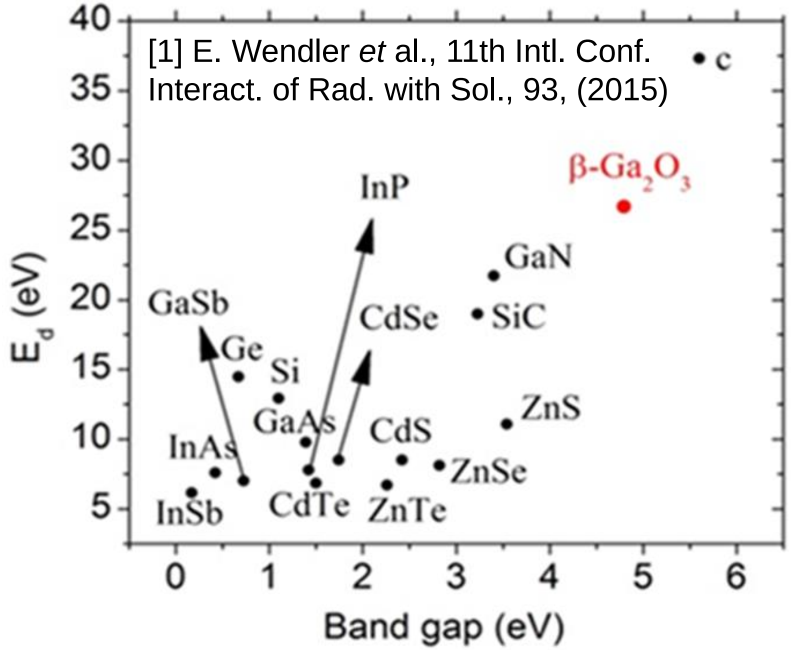
Wide and ultra-wide bandgap semiconductors







[1] E. Wendler *et* al., 11th Intl. Conf. Interact. of Rad. with Sol., 93, (2015)

Applications of WBG semiconductors:

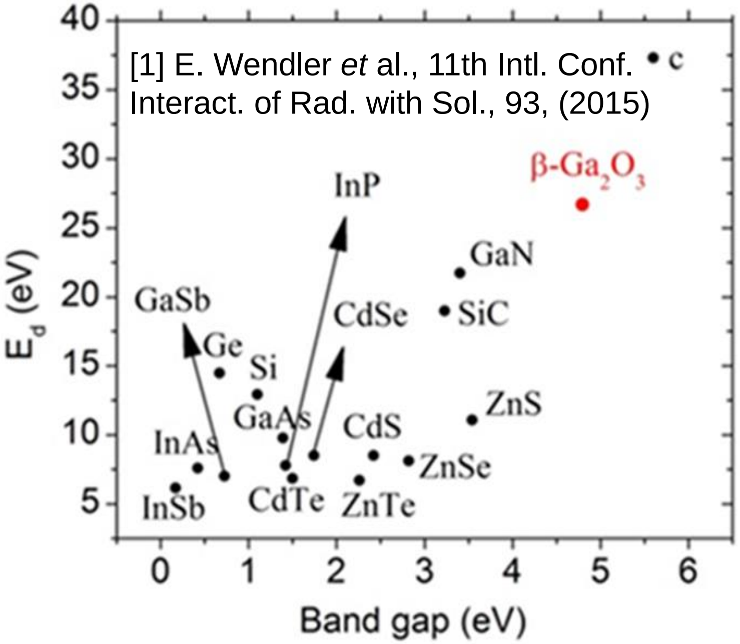
- **Power electronics** – energy efficiency
- **High-frequency** – radar/5G/mm-wave
- **Solid-state LED lighting**
- **UV emitters** – disinfection and health
- **UV detectors** – for safety/sensing
- **Radiation-hard** – Space/nuclear harsh environment applications
- **High temperature** – Large bandgap energy allows operation up to 1000°C

WBG Semiconductors (GaN, SiC) are the MOST important semiconductors after Silicon

Several major companies are invested in WBG technology – Apple, Intel, Texas Instruments etc.

β-Ga_2O_3 material properties

Properties	Si	SiC	GaN	β-Ga_2O_3
E_g (eV)	1.1	3.2	3.4	4.7
Max F_{BR} (MV/cm)	0.2	2	3.3	8*
Substrate cost	Low	Medium	High	Low*
Heterojunction	Yes	No	Yes	Yes
Mobility (cm^2/V.s)	600	600	1000-2000	200
Thermal Conductivity ($Wm^{-1}K^{-1}$)	13	270	28	0.1-0.27



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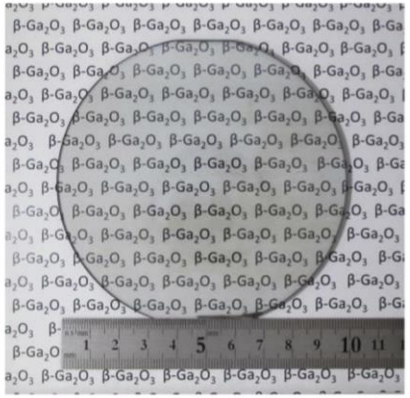
- The only wide bandgap material with controllable doping that can be grown from the melt
  - Enables low defect-density, large area wafers/epitaxial growth
- Ease of n-type doping over a wide range reported (10^{14} – 10^{20} cm^{-3})
- Higher breakdown field and point-defect formation energy when compared to other WBG technologies can enable low-loss, radiation-hard devices for power switching and high-power RF applications



4 in. β-Ga_2O_3 single-crystal wafer

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Radiation effects in a wide bandgap transistor

WBG materials are intrinsically more radiation-hard than Si devices due to higher ionic bond strengths between atoms

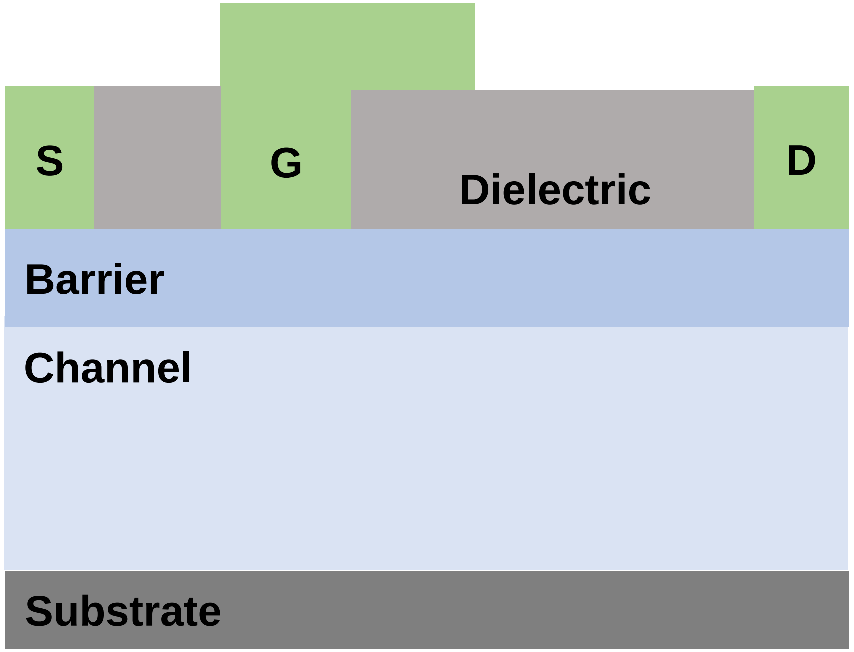
WBG devices (such as AlGaN/GaN HEMTs and β-Ga_2O_3 FETs) are quite different from conventional Si MOSFETs:

Structure

- Instead of a gate oxide, semiconductor heterojunction is used
- The layers below the channel are insulating (undoped)

Function

- High electric fields are applied between gate and drain for RF/power
- High electric field underneath the gate



Wide Bandgap Transistor Structure

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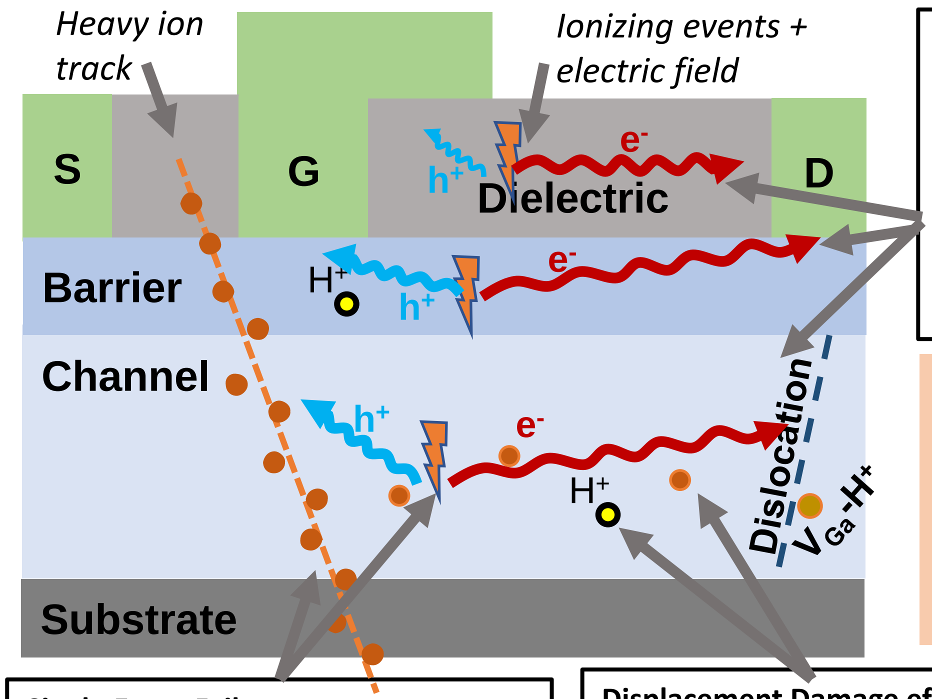

Cumulative Ionizing Dose effects

- Hole release/capture in gate and passivation dielectric,
- Charging in AlGaN cap layer
- Trapped charges in buffer regions
- Hydrogen release, migration in buffer, AlGaN and dielectric layers
- Charging/discharging of pre-existing defects

DEVICE IMPACTS OF RADIATION

- Degradation of transport properties
- Threshold voltage shift
- RF-DC dispersion/knee walkout
- Degraded leakage current/breakdown
- Degradation in I_{MAX}/g_m
- Lower f_T, f_{MAX}, gain, linearity

Single Event Failure

- Ion tracks, point defect generation
- Gate dielectric/barrier rupture
- Electron-hole induced avalanche breakdown

Displacement Damage effects

- Creation/migration of point defects in channel/buffer/dielectric
- Release and migration of hydrogen
- Impact of existing point/extended defects

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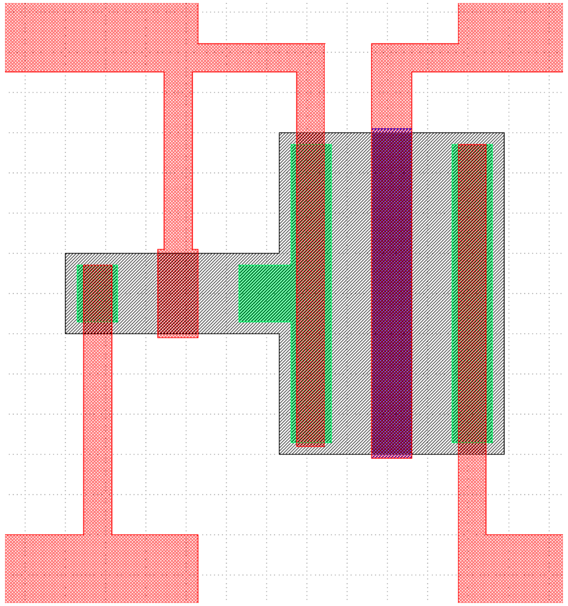
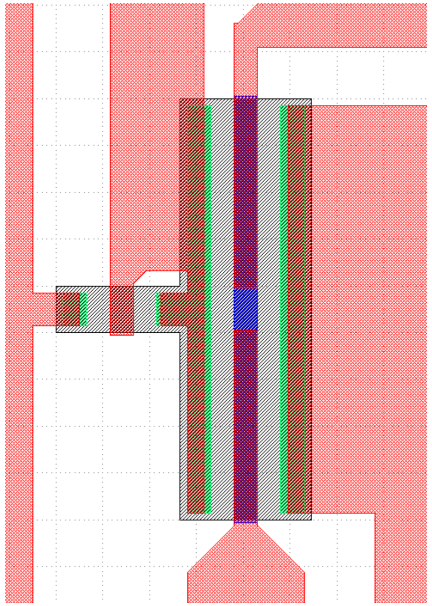
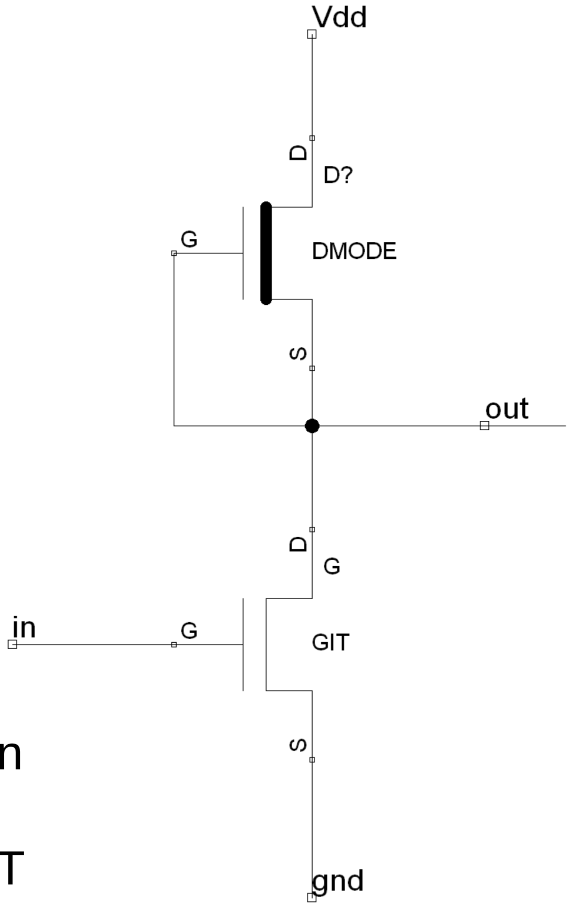
Prior work: AlGaN/GaN-based Radiation Tolerant Logic Circuits



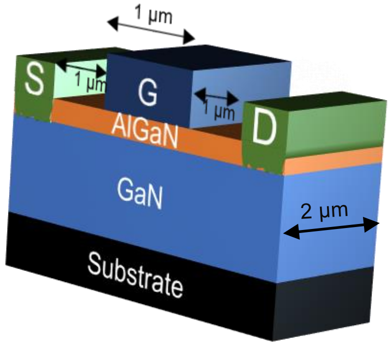
DCFL Inverter Layout



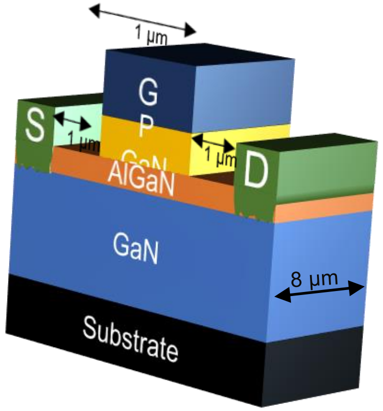
DCFL NOR Gate Layout



DCFL Inverter Schematic



D-Mode Device



E-Mode Device

- A process flow was developed at OSU for logic circuits on an AlGaN/GaN platform
- Since p-channel devices are not efficient, direct-coupled FET logic (DCFL) monolithically integrating enhancement-mode and depletion-mode devices is used
- The platform supports logic gates (NOT, NOR, NAND) and RF HEMTs

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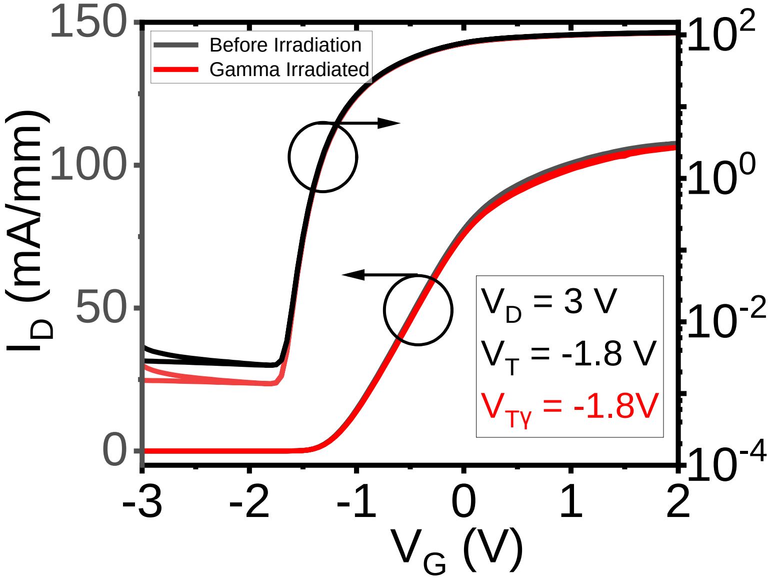
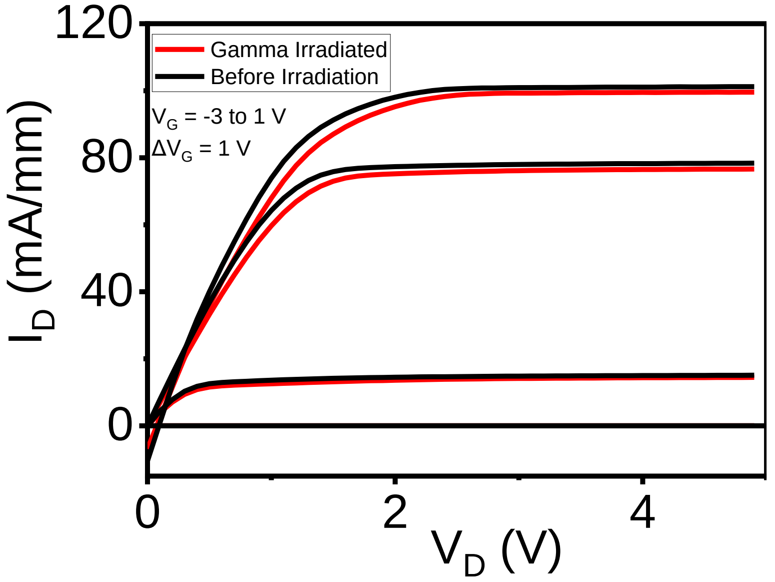
Prior work: AlGaN/GaN-based Radiation Tolerant Logic Circuits

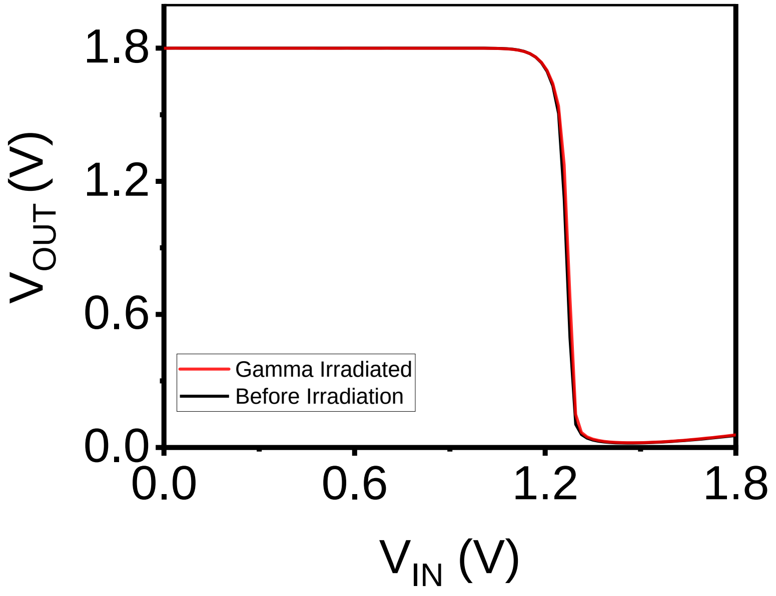
D-Mode Transfer Characteristics



D-Mode Output Characteristics



Inverter Voltage Transfer Characteristic



- AlGaN/GaN D-Mode transistors, E-Mode transistors and logic gates were fabricated and gamma irradiated
  - Accumulated dose of 5.04 Mrad
- Electrical characterization post-rad show little to no degradation in device performance
- Compact models were developed for devices to enable radiation-hard circuit design in Cadence Virtuoso

Transitioned to Oakridge National Laboratory under a recently funded NEET project for GaN-based sensing circuits (Milton Ericson, Kyle Reed, Dianne Ezell)

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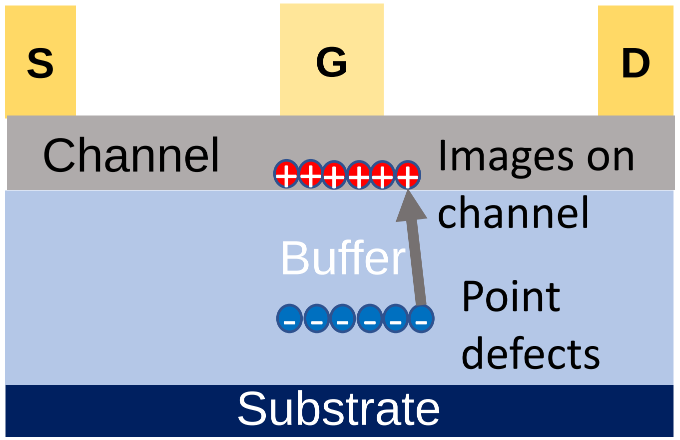
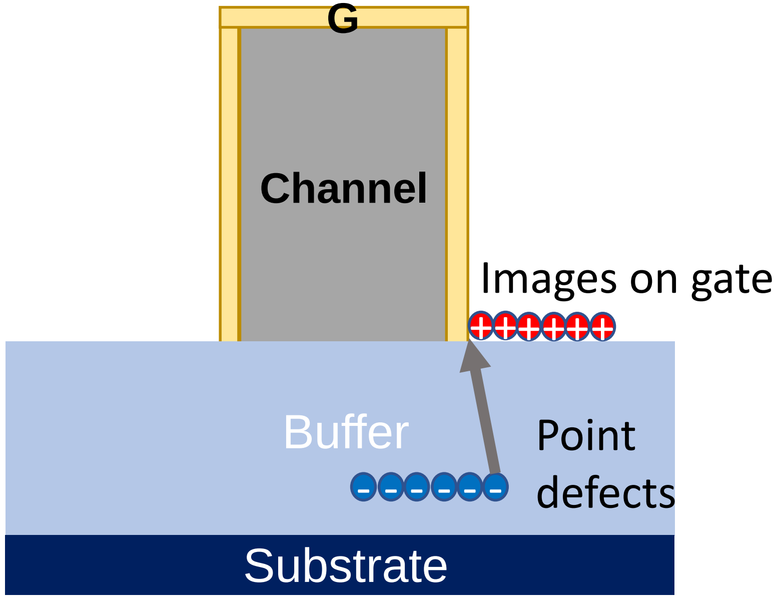
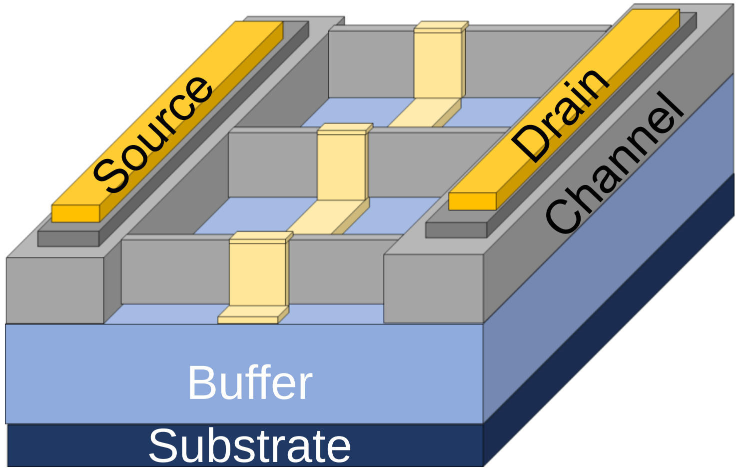
Fin device geometry for increased radiation tolerance



Planar Device



Fin Cross-Section



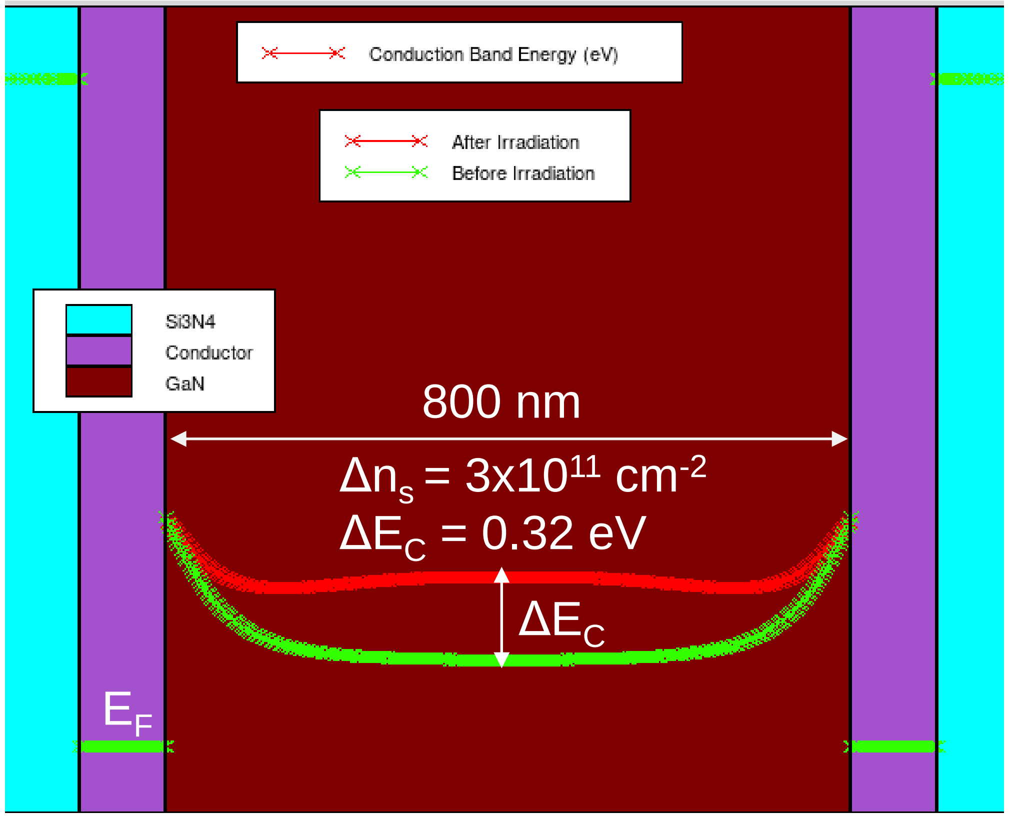
Fin Device

- In a planar device, radiation-induced point defects in the buffer are electrostatically imaged in the channel
  - Leads to threshold shift and reduction in channel charge

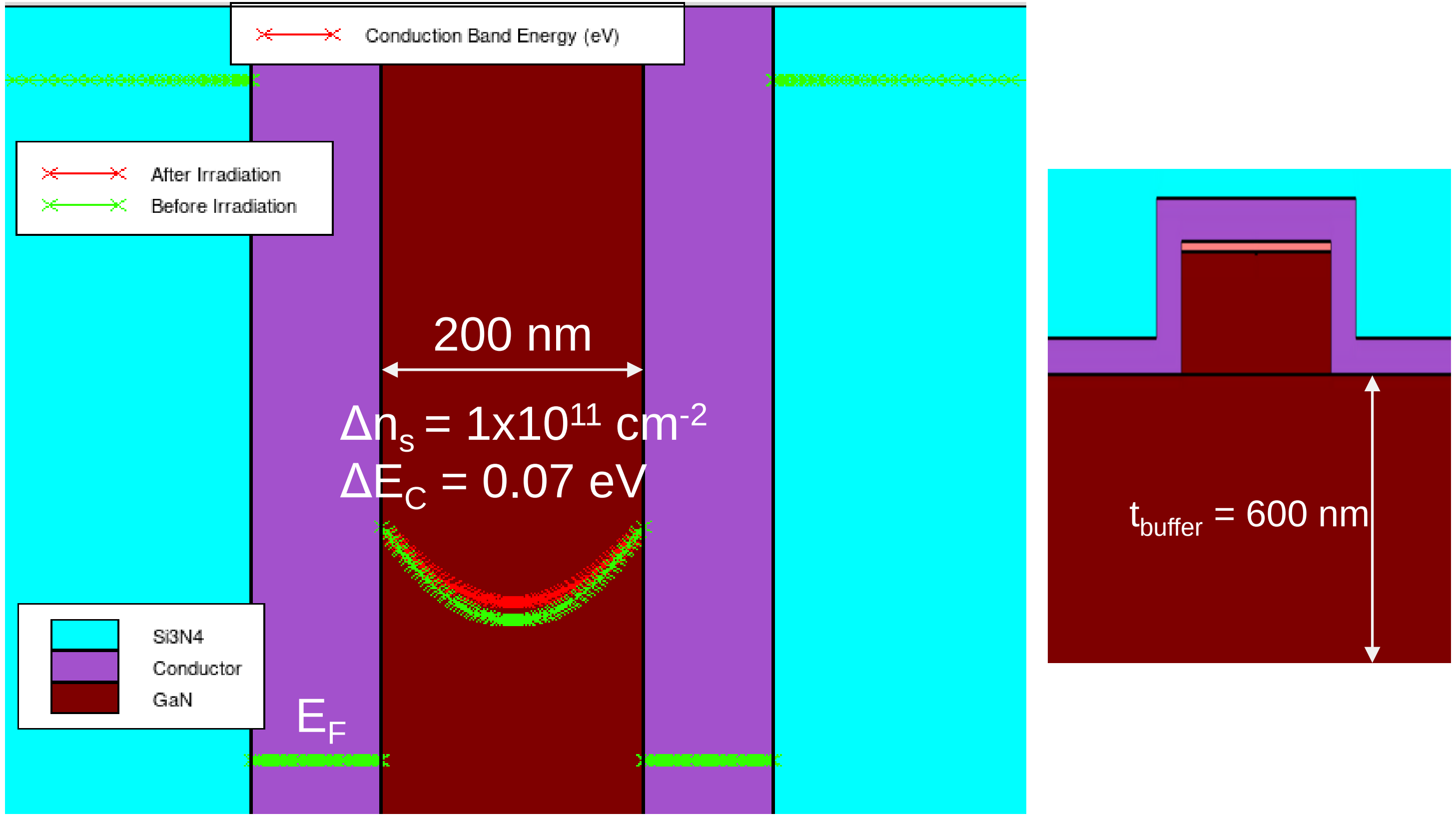
- For fin device geometries, side gate electrostatically screens the channel from defects in the buffer

Effect of scaling fin width on electrostatics

Fin cross section: W_{fin}= 800nm



Fin cross section: W_{fin}= 200 nm



- To understand the effect of scaling fin width on electrostatics, the equilibrium band diagram for AlGaN/GaN FinFETs with different fin widths was modeled in Silvaco TCAD
  - Uniform doping of $1x10^{16}$ cm^{-3} mid-gap acceptor states was used to model radiation-induced defects
- Thinner fins show smaller increase in conduction band energy when acceptors are introduced
  - Results in lower ΔV_T and smaller reduction in channel charge due to higher electrostatic control of gate

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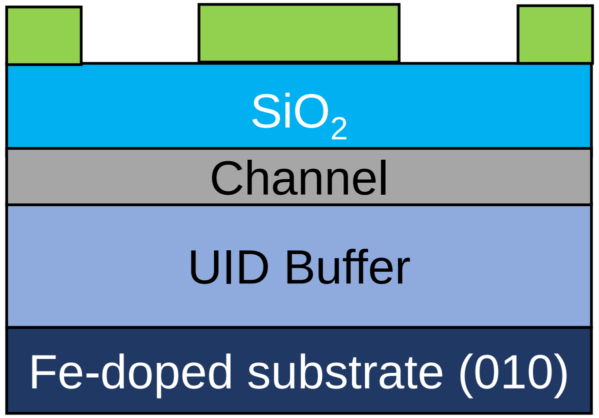
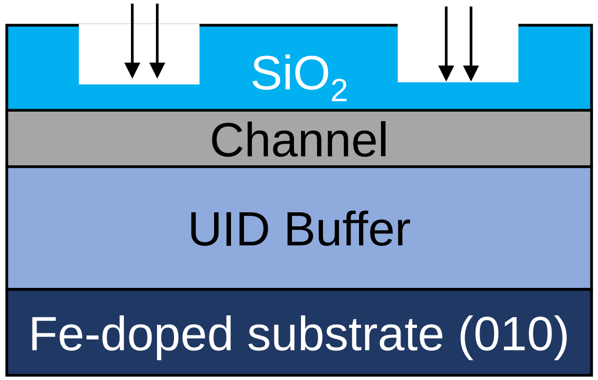
Process flow – MOCVD regrown contacts

Side View



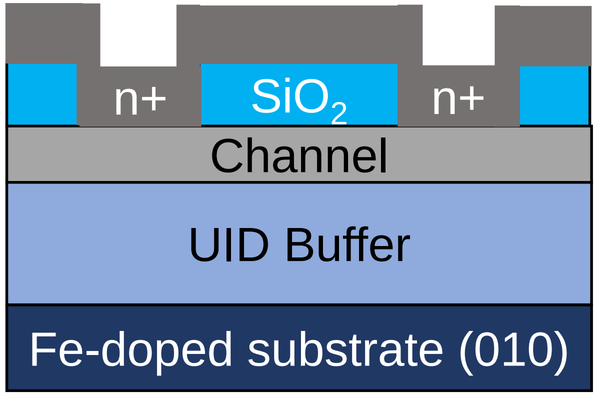
- Pattern PR by optical lithography on top of PECVD SiO_2 hard mask for source/drain n+ regrowth
- $CF_4/Ar/O_2$ based dry etch of SiO_2

Side View



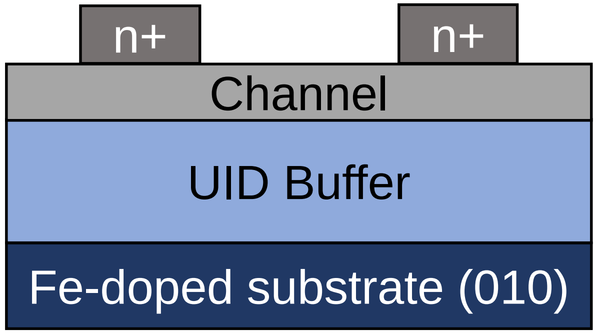
- Dilute buffered oxide etch (1:15) down to channel surface to avoid damage

Side View



- 50 nm MOCVD regrowth
  - $N_D = 1x10^{20}\ cm^{-3}$

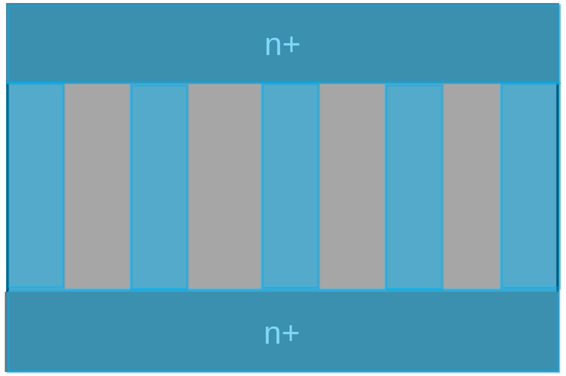
Side View



- Regrowth liftoff in undiluted BOE and HF Dip (1:10)

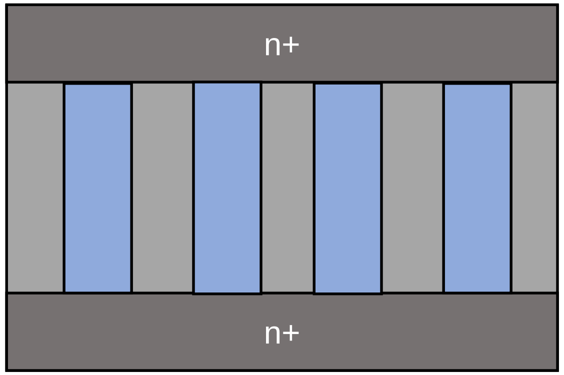
Process flow – β-Ga_2O_3 FinFETs

Top View



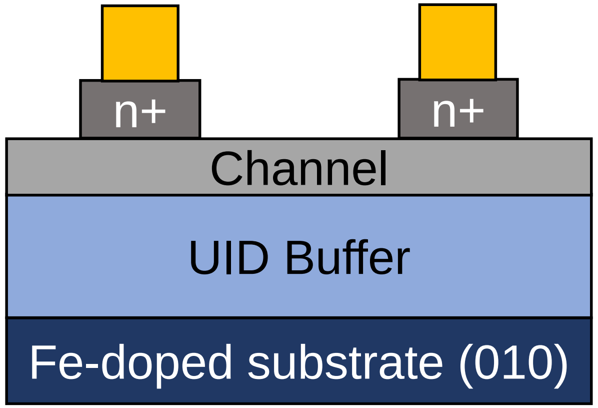
- Define fin spacing by electron-beam lithography and CHF_3/Ar based dry etch of SiO_2 hard mask

Top View

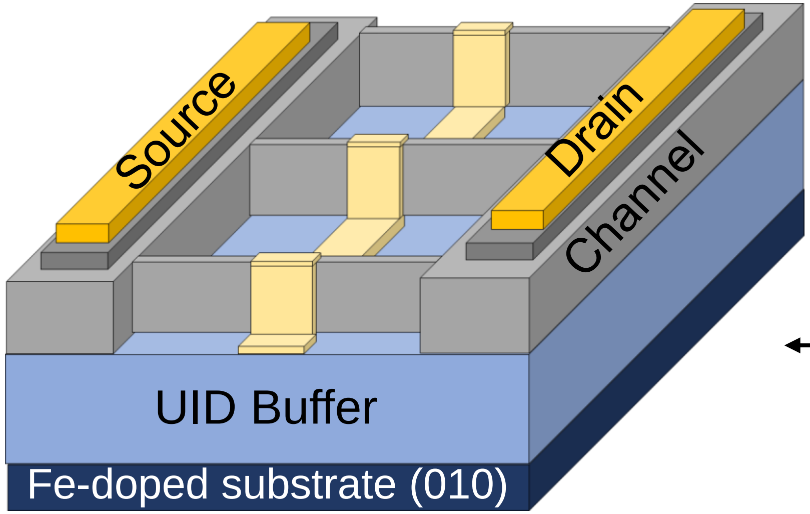


- Damage-free etch of stripes using atomic Ga flux *in-situ* (in MBE chamber)

Side View

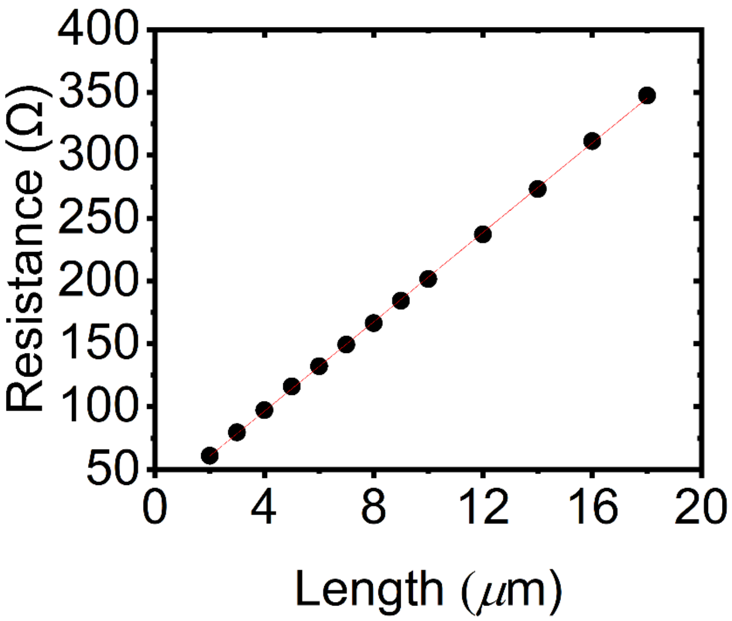


- Electron-beam evaporation of Ti/Au ohmic contacts
- Rapid thermal anneal in N_2 ambient

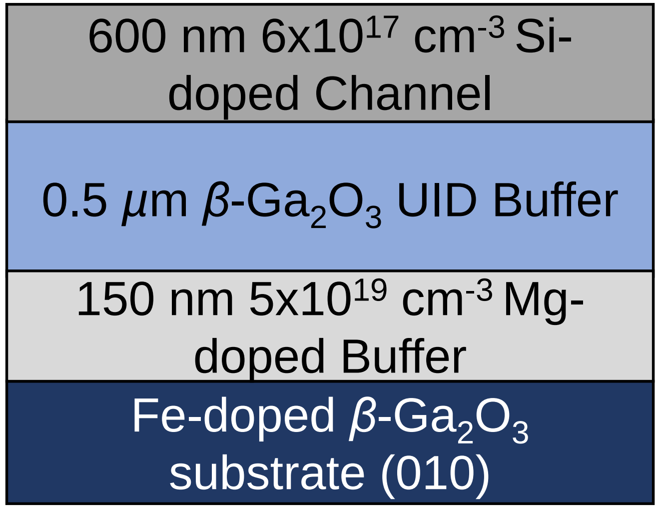


- RF sputtering of Ni Schottky gates

High n_s MOCVD epitaxial structure



Epitaxial structure grown by Dr. Zixuan Feng (OSU)



600 nm 6×10^{17} cm^{-3} Si-doped Channel

0.5 μm β-Ga_2O_3 UID Buffer

150 nm 5×10^{19} cm^{-3} Mg-doped Buffer

Fe-doped β-Ga_2O_3 substrate (010)

Transfer-Length Measurement (TLM)

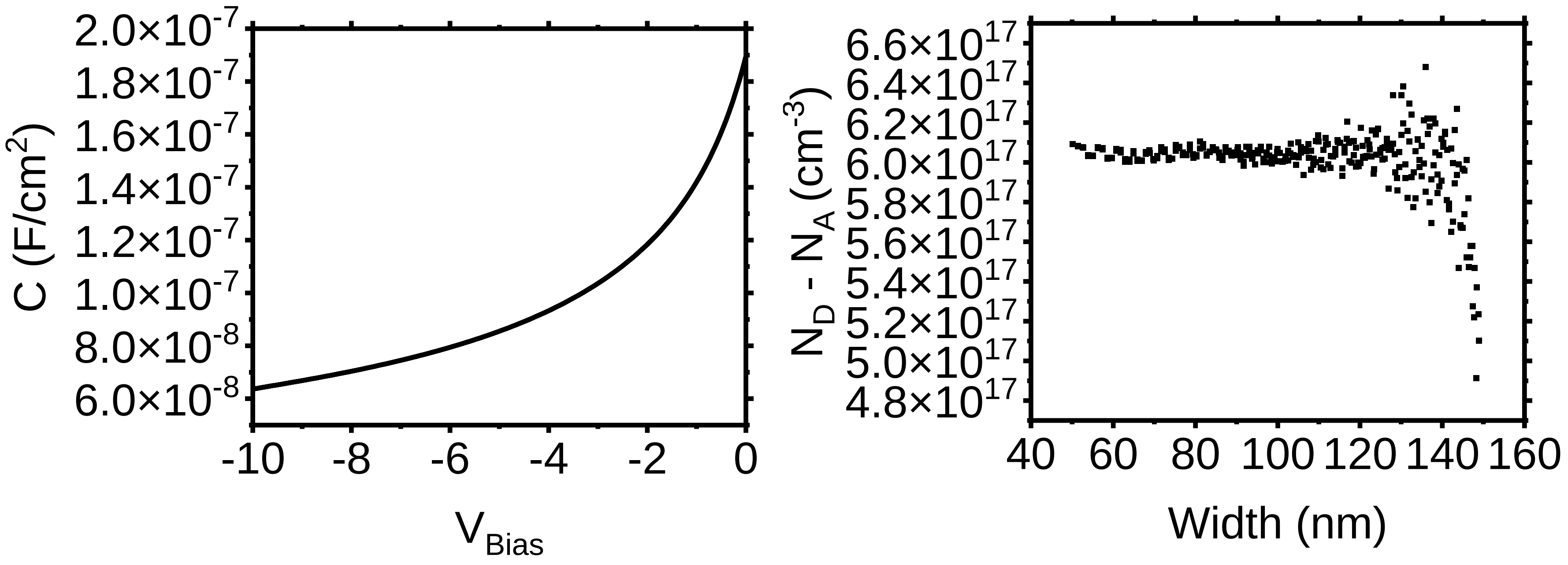
$R_C = 1.27$ Ω.mm
$R_{Sh} = 1.77$ kΩ/sq
$\rho_C = 9.11 \times 10^{-6}$ $\Omega.cm^2$

Hall Measurement

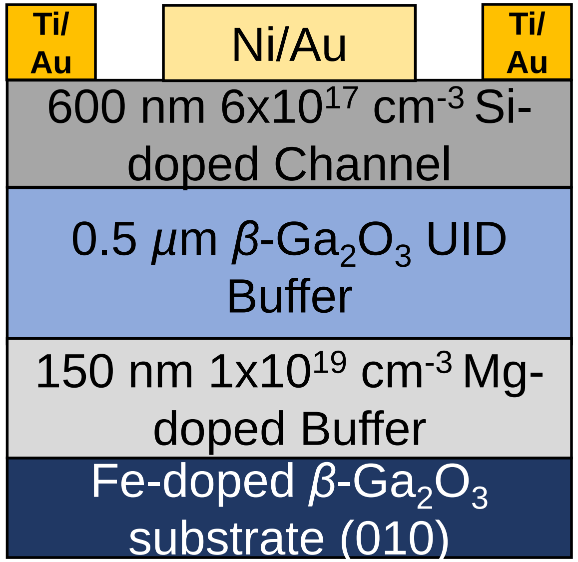
$\mu_n = 134$ $cm^2/V.s$
$R_{sh} = 2.03$ kΩ/sq
$n_s = 2.28 \times 10^{13}$ cm^{-2}

- Insulating buffer layer achieved through Mg doping at regrowth interface
- Hall data and TLM show good agreement in terms of R_{Sh}
- High n_S of 2.28×10^{13} cm^{-3} is achieved with R-T mobility of 134 $cm^2/V.s$

Capacitance-voltage measurements



C-V structure



Ti/Au

Ni/Au

Ti/Au

600 nm 6x10^{17} cm^{-3} Si-doped Channel

0.5 μm β-Ga$_2$O$_3$ UID Buffer

150 nm 1x10^{19} cm^{-3} Mg-doped Buffer

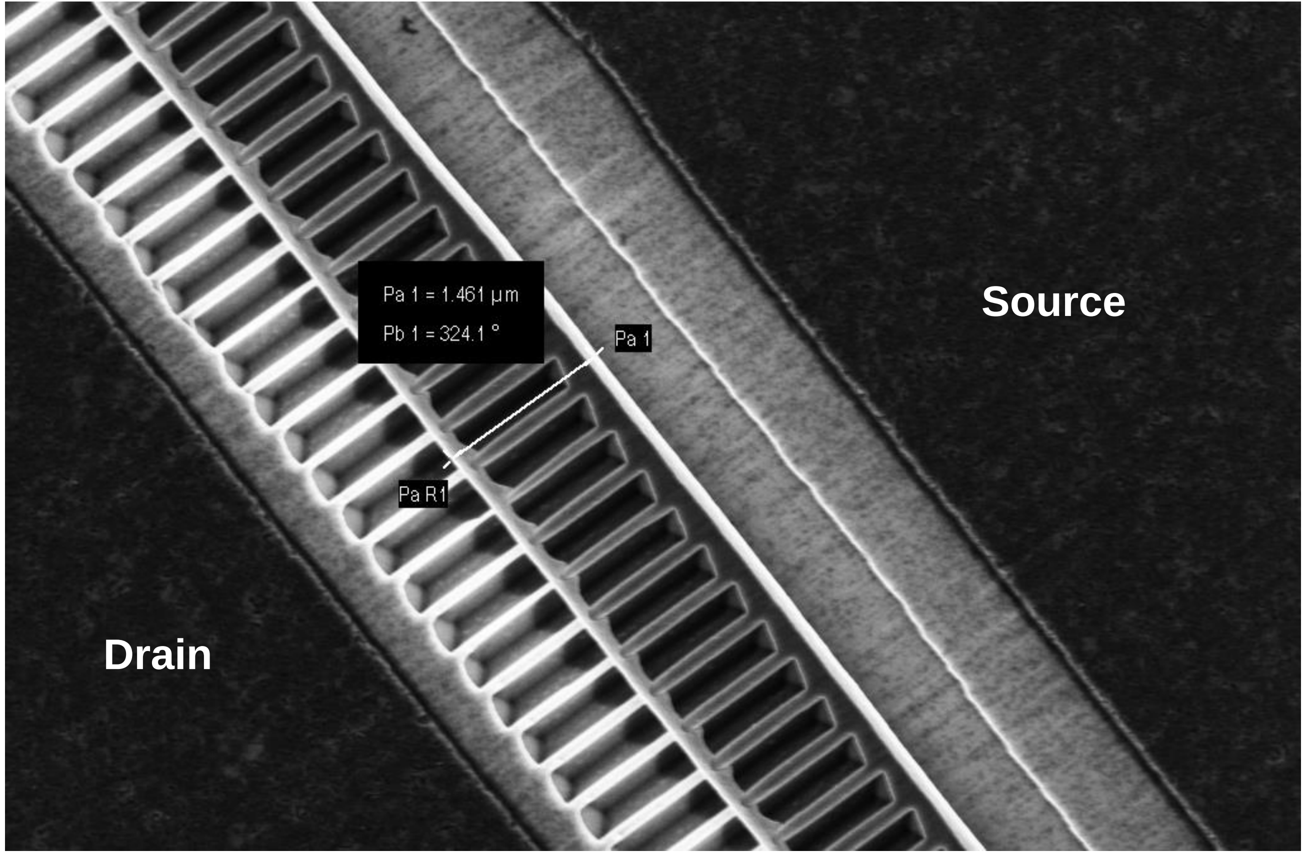
Fe-doped β-Ga$_2$O$_3$ substrate (010)

- Parallel plate Capacitance-Voltage measurements carried out on circular 100 μm radius sputtered Nickel Schottky contacts surrounded by Titanium/Gold ohmic contact

- Limited to -10 V due to reverse leakage

- Extracted doping density is 6x10^{17} cm^{-3}

Scanning-electron microscope image of device



- High-aspect ratio fins patterned by damage-free atomic Ga flux etching technique developed at OSU - N.K. Kalarickal *et* al*.* Appl. Phys. Lett. **119** (2021)
  - Performed *in-situ* in MBE chamber
  - $4Ga(s) + Ga_2O_3(s) \rightarrow 3Ga_2O(g)$
- RF sputtering process deposits Ni gates conformally
- Electron-beam lithography enables scaled w_{fin} = 200 nm with pitch of 400 nm

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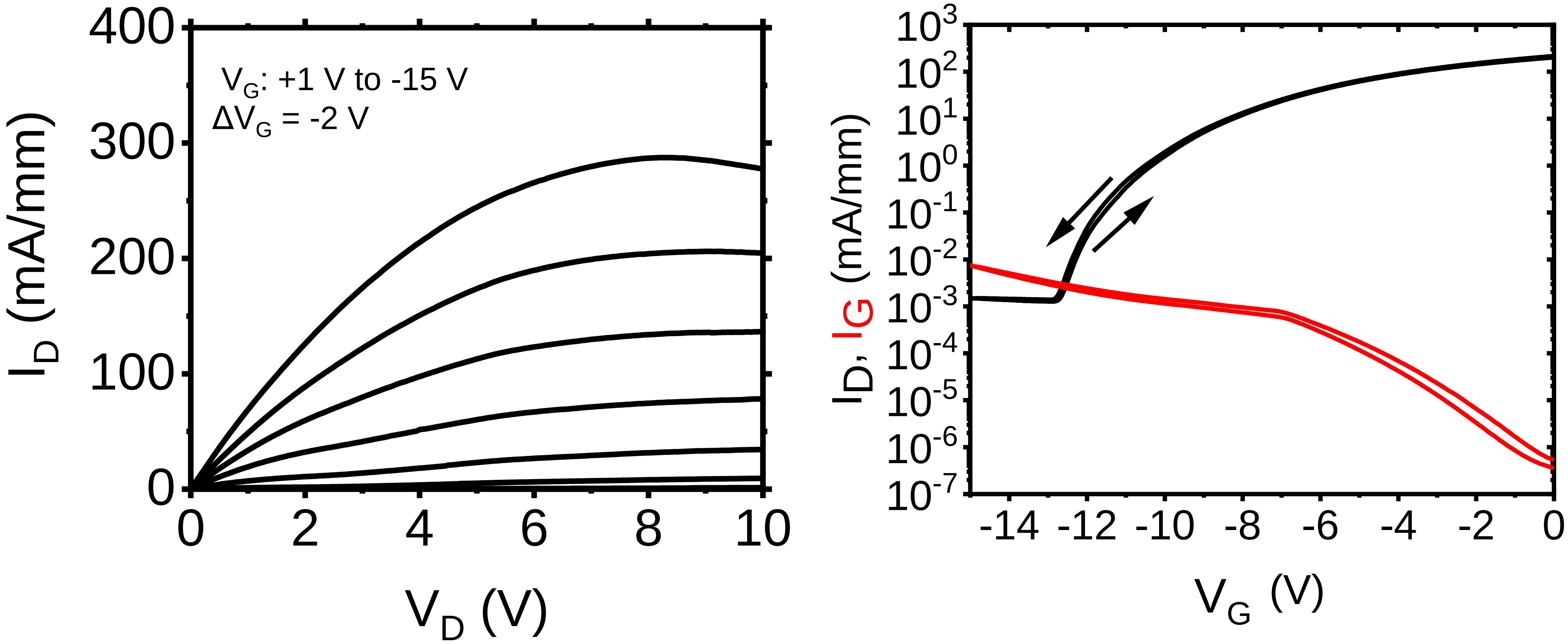
β-Ga_2O_3 FinFETs – DC output and transfer characteristics



- Current-density above 200 mA/mm normalized to fin width

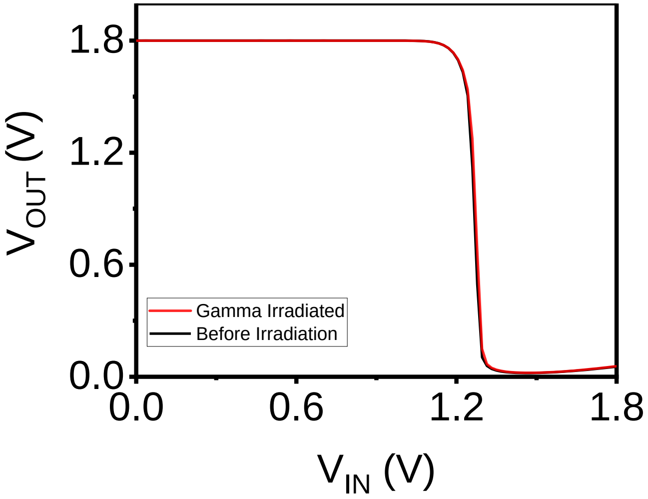
- 10^5 on/off ratio achieved at V_T = -13 V
  - Limited by leakage of gate Schottky diode

Conclusion & future work

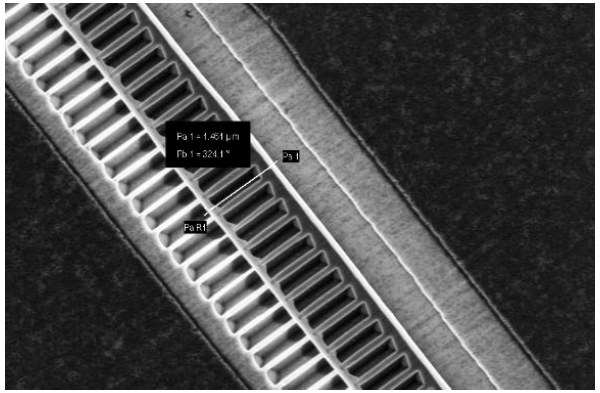
- Cleanroom process flow and compact models for radiation-hard GaN digital logic circuits were developed
  - Project transitioned to Oakridge National Laboratory under NEET program

- *β*-Ga_2O_3 FinFET device with inherently better tolerance to radiation was demonstrated
  - Plan to irradiate both AlGaN/GaN and *β*-Ga_2O_3 FinFETs at OSU nuclear reactor and compare to similar planar devices

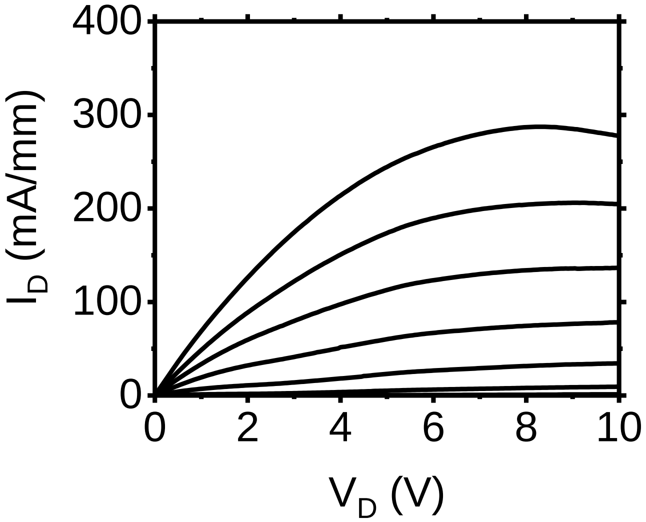
Fabricated DCFL Inverter



Inverter Voltage Transfer Characteristic



SEM image of β-Ga_2O_3 FinFET



Output Characteristics of β-Ga_2O_3 FinFET

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