Indian Institute of Technology Bombay

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Device engineering for β-Ga_2O_3-based high power electronics

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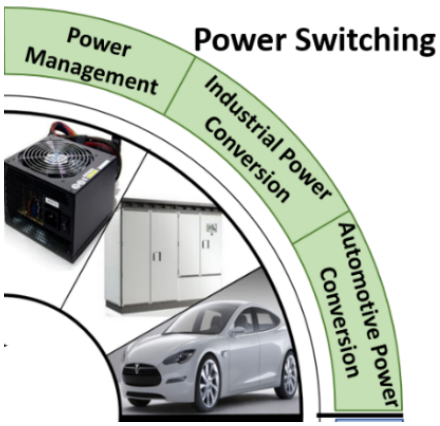
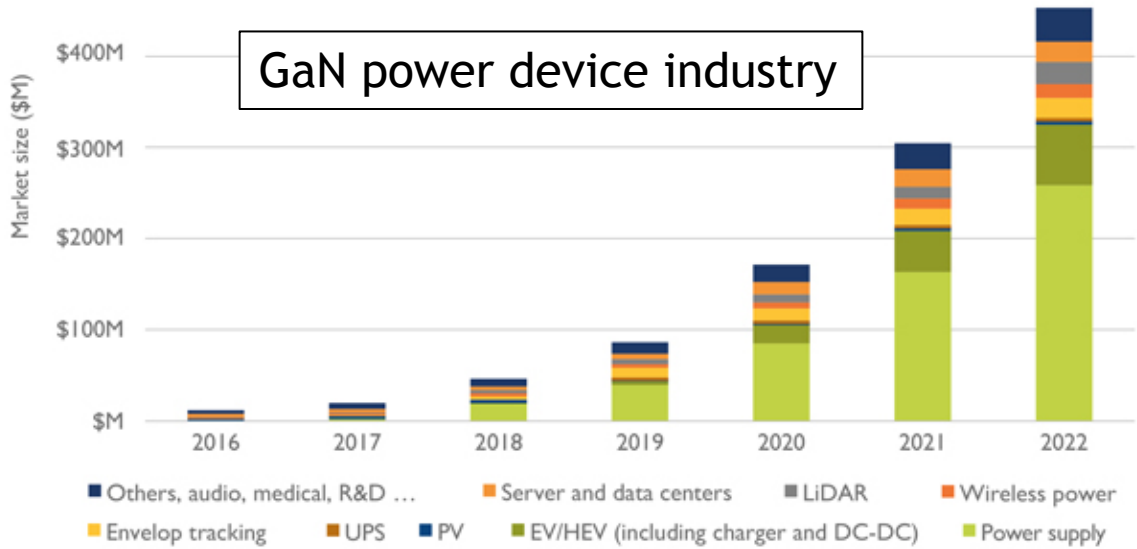
Outline

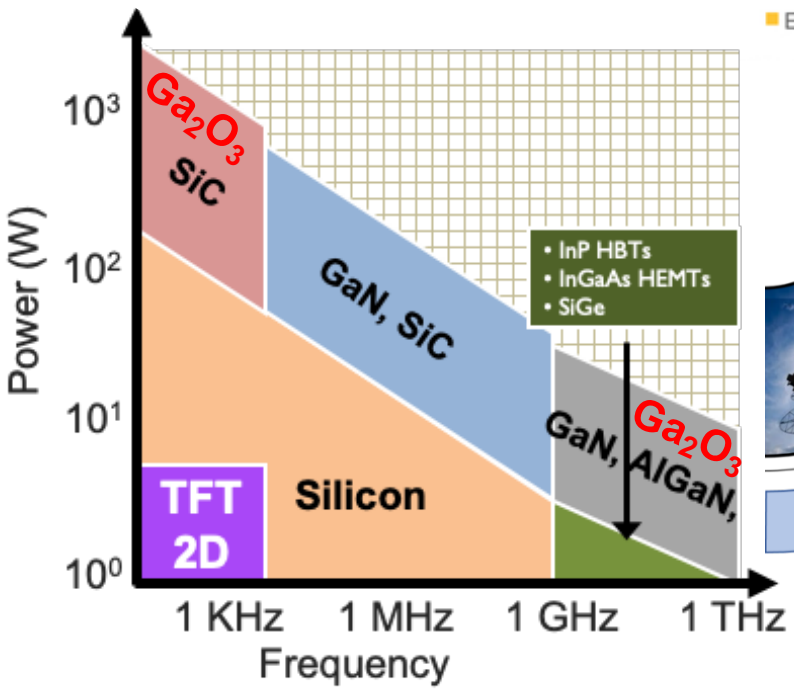
- β-Ga_2O_3: Background and motivation
- Device fabrication/characterization
  - Modulation doped FETs
  - Delta doped MESFETs
  - Enhancement-mode MOS Capacitors
- Conclusions

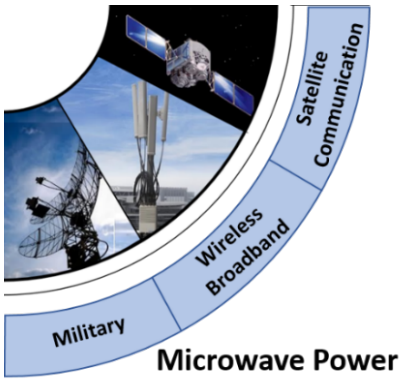
Power devices: application space

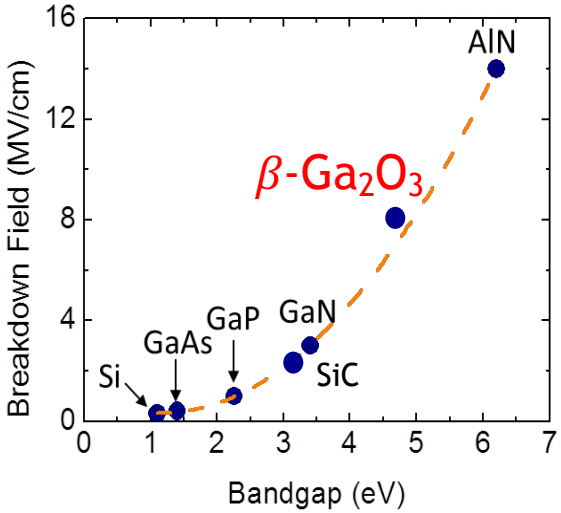




Yole development 2019





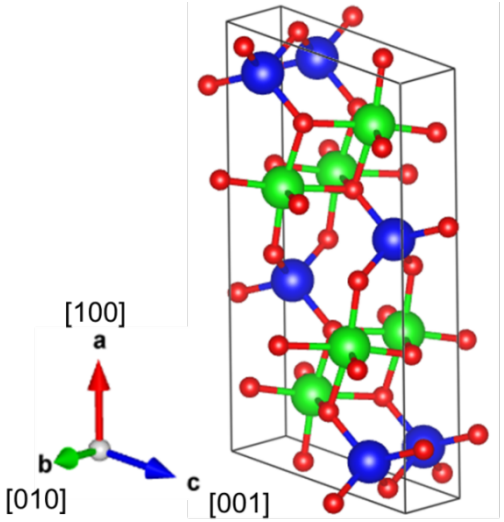


Technology opportunities:

- o power switching applications
- o mm-wave power

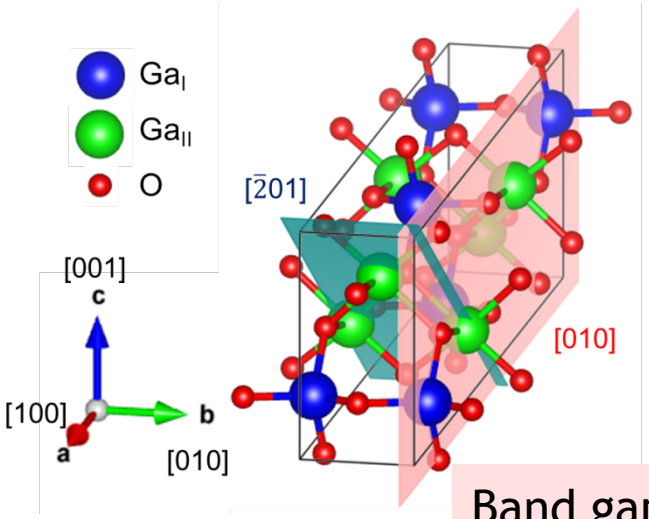
β-Ga_2O_3: Introduction

β- phase: Monoclinic crystal structure
Other polymorphs : *α*, *γ*, *δ* and ε



Ga_I
Ga_{II}
O

Lattice constants	
a	12.214 Å
b	3.0371 Å
c	5.7981 Å
α	90°
β	103.83°
γ	90°

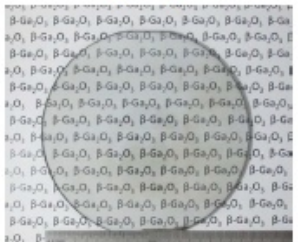


Band gap = 4.6 eV

Edge-defined film-fed growth

TAMURA

4" Ga_2O_3 wafer



A. Kuramata *et al.*, Jpn. J. Appl. Phys. **55**, 1202A2 (2016).

Czochralski

IKZ

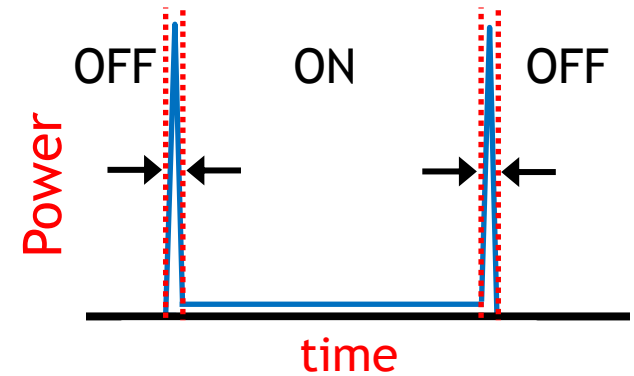
2" Ga_2O_3 wafer

Z. Galazka *et al.*, J. Cryst. Growth **404**, 184 (2014).

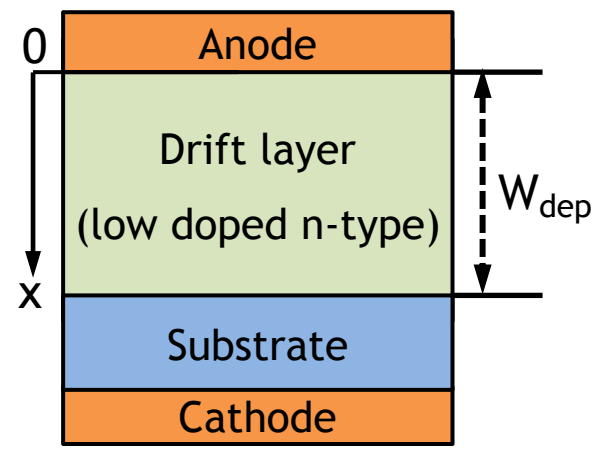
- **Melt-based growth techniques**
  - **First wide-band gap material**
  - High quality low cost native substrates
- **Homo-epitaxy** ✓
  - Low defect density
- **Controlled n-type doping** (Si, Sn, Ge)/ insulating (Fe, Mg) films
- $\rho = 10^{-3} - 10^{12}$ Ω.cm, $n = 10^{14} - 10^{20}$ cm^{-3}
- **p-type Ga_2O_3** ?

Power switching parameters

- **R_{ON} (on-state resistance)**
  - Conduction loss
  - Dominance at low frequencies
- **Q_g (gate-charge)**
  - Charges to drive the ON-OFF transition
  - Switching loss
- **V_{BR} (Breakdown voltage)**
  - Max voltage the device can block in off-state



$$P_{loss} \sim I_{out}^2 R_{ON} + I_{out} V_{in} \frac{Q_g}{I_g} f_{sw}$$



$$R_{on} = \frac{W_{dep}}{q\mu_n N_D} = \frac{4V_{BR}^2}{\varepsilon_s \mu_n E_C^3}$$ → Baliga's FoM

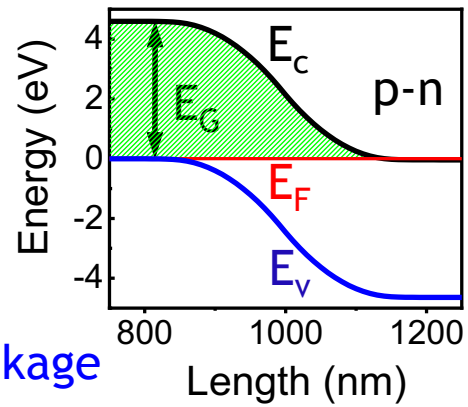
$$R_{on} Q_g = \frac{4V_{BR}^2}{\mu_n E_C^2}$$ → Baliga's high frequency FoM

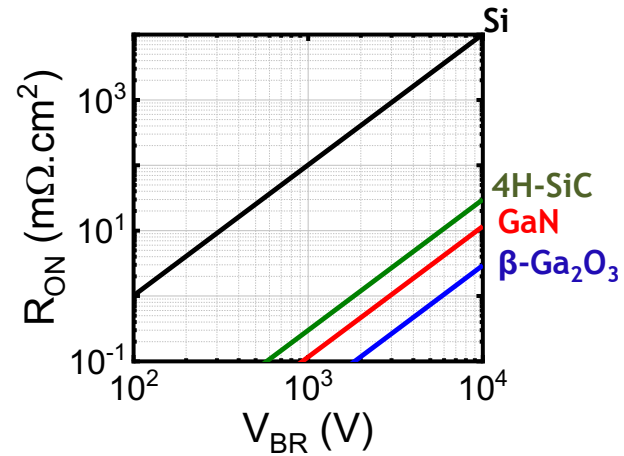
FoM's calculated for E_C = 8 MV/cm, μ_n = 250 cm²/Vs

Properties	Si	GaAs	4H-SiC	GaN	Ga_2O_3
Baliga's FoM ($\varepsilon\mu E_C^3$)	1	16	250	870	**2916**
Baliga's high freq. FoM (μE_C^2)	1	11	46	100.8	**118.5**

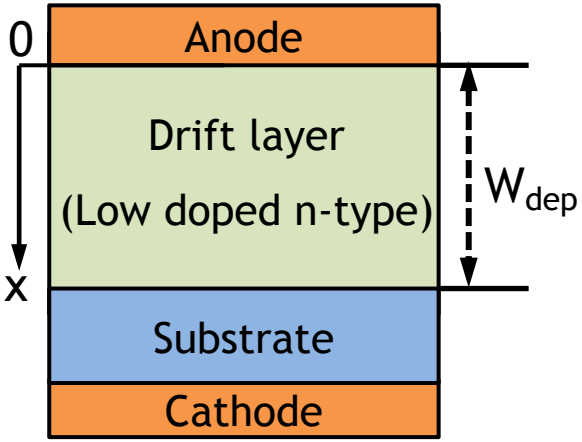
Critical electric field

- **Device metrics**
  - Low R_{ON} for a given V_{BR}
- **Predicted E_C = 8 MV/cm**
  - p-n band-to-band tunneling
- **Real picture**
  - E_C ~ 3-4 MV/cm: Schottky leakage

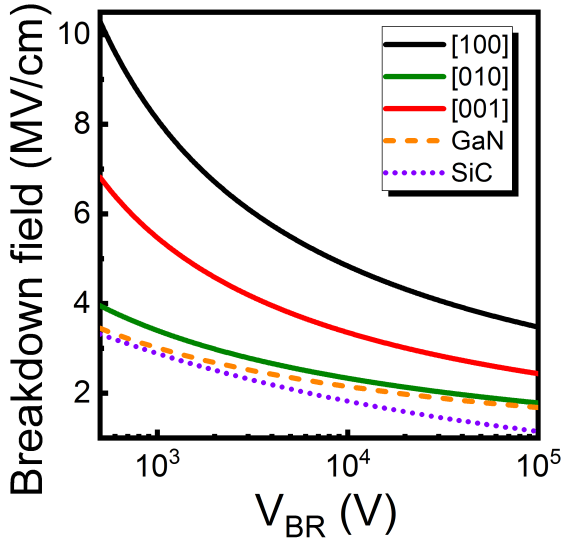


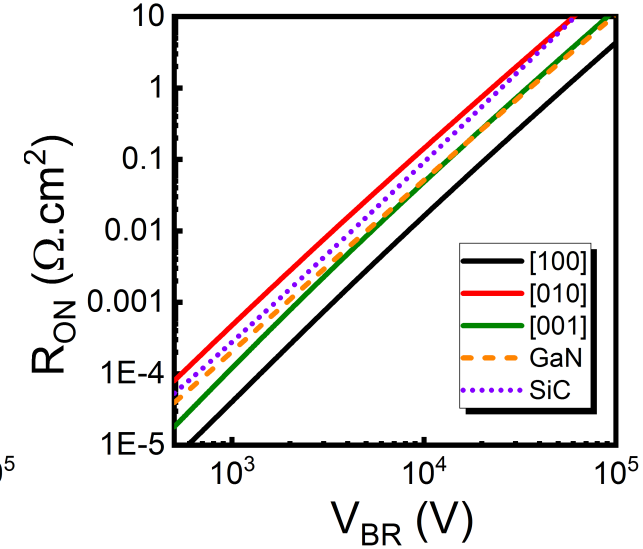


- **<u>Breakdown field calculation (unipolar device)</u>**
  - Avalanche breakdown
    - Upper limit on device performance

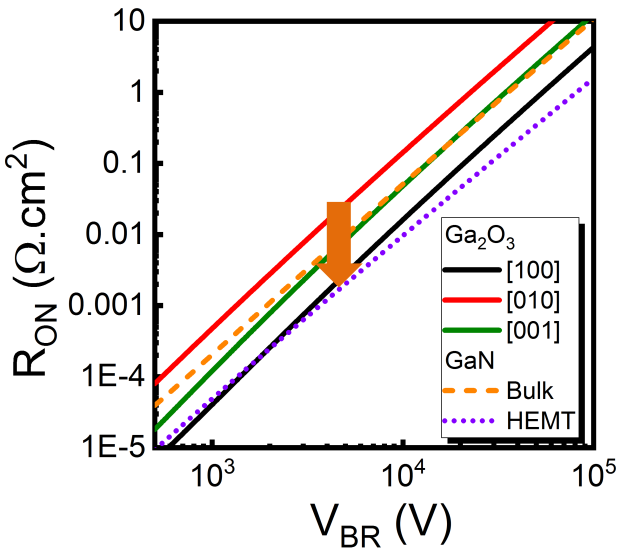


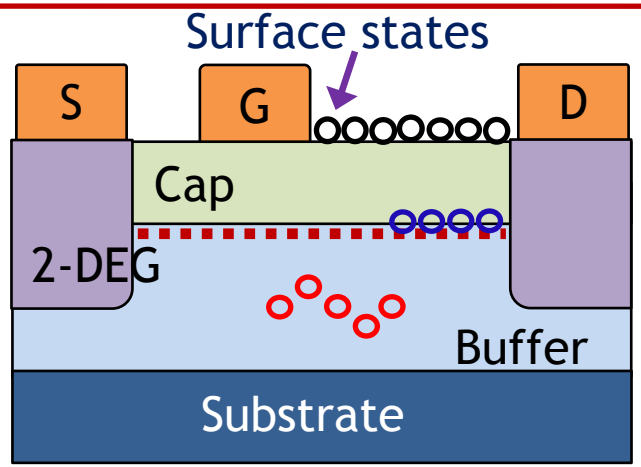
Credit: Zhanbo Xia

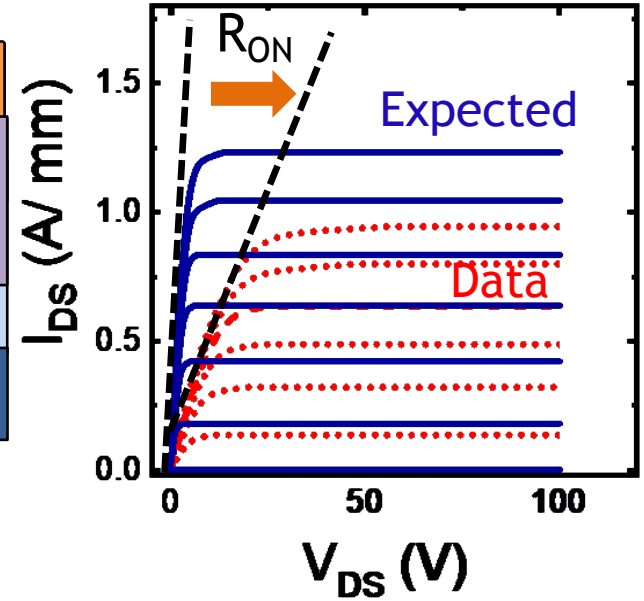




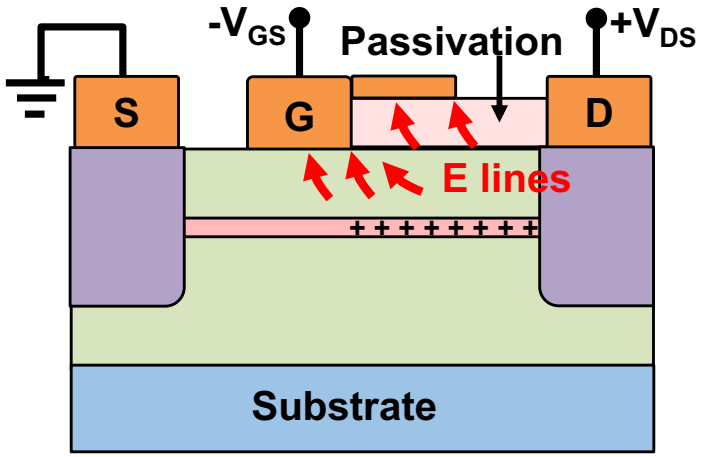
Importance of carrier mobility







- **AlGaN/GaN HEMTs**
  - Lateral power devices
- **Ga_2O_3 heterojunction capability** ✓
- **Design of $(AlGa)_2O_3/Ga_2O_3$ FETs.**
- **Lateral power devices**
  - Degradation in R_{ON} => dynamic R_{ON}
  - Peak field at gate edge
- Field-plate (FP): additional electrode for E lines termination
- **Power switching: Enhancement-mode operation**



Outline

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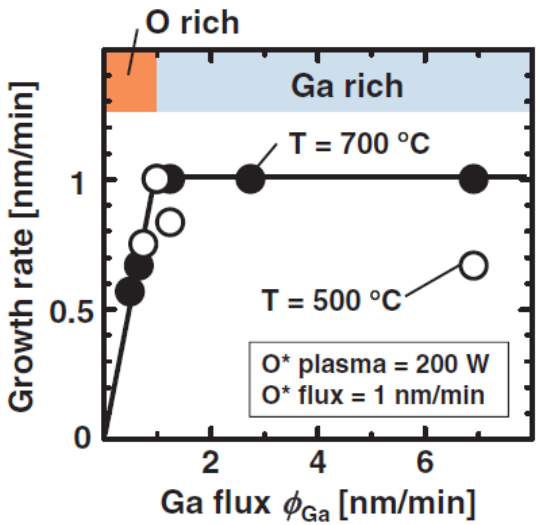
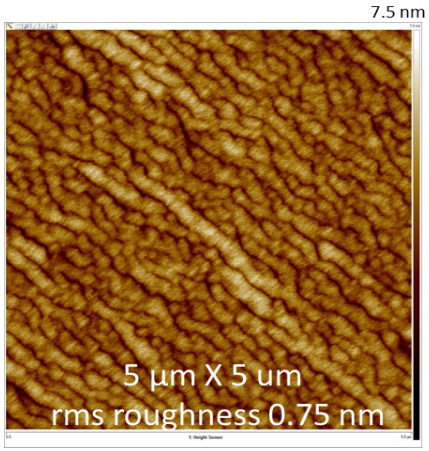
  - Delta doped MESFETs
  - Charge trap layer: e-mode devices
- High-k/bilayer dielectric field management
- Conclusions

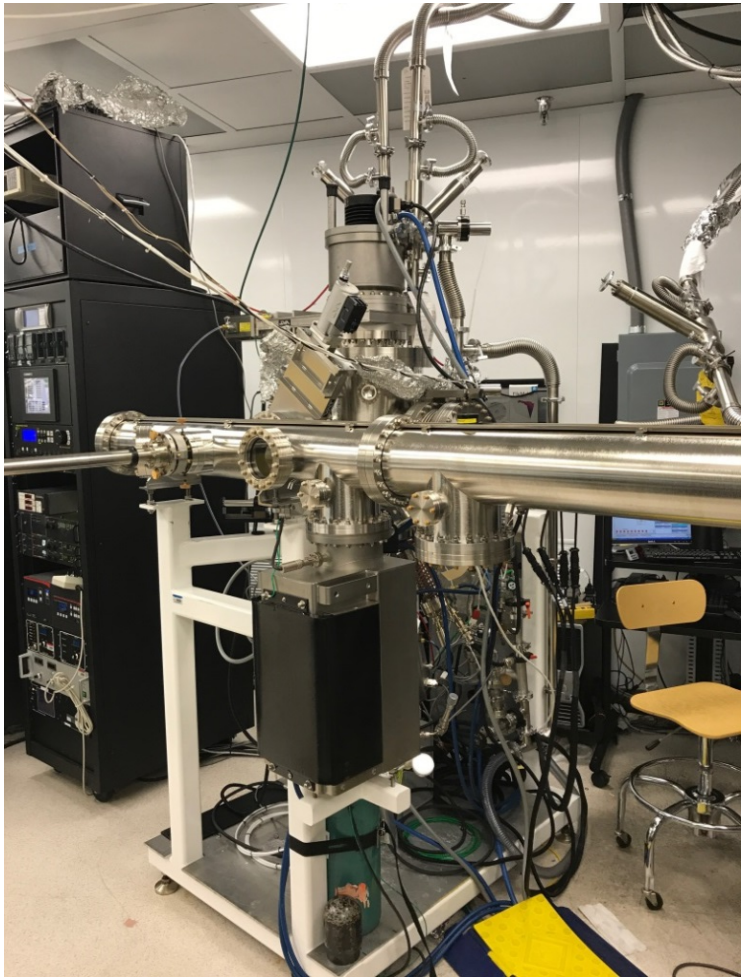
MBE growth of β- Ga_2O_3 (OSU)

- Substrate: Bulk (010) β- Ga_2O_3
- Substrate Temperature: 700° C
- O_2 plasma power : 300 W
- Ga flux: 8×10^{-8} Torr (O-rich conditions)
- Chamber pressure: 1.5×10^{-5} Torr
- Growth Rate: 240 nm/ hour



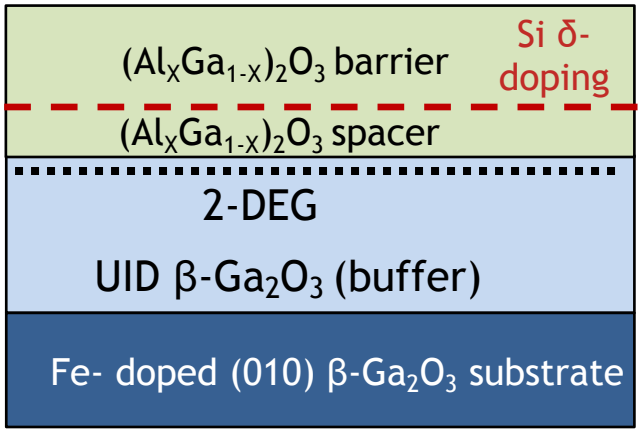
Okumura et. al.
(Speck Group- UCSB)

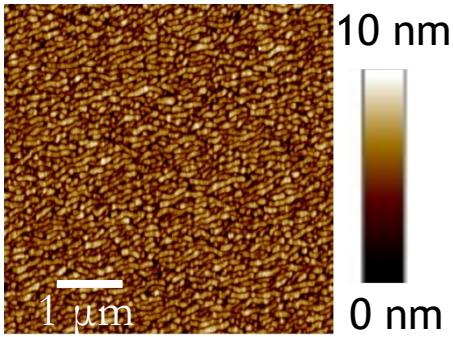


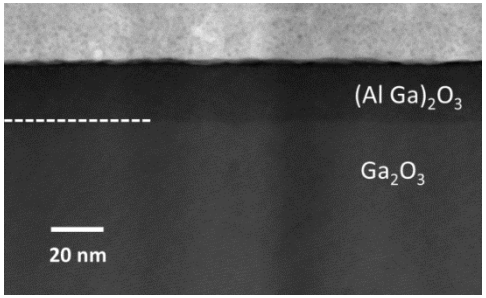


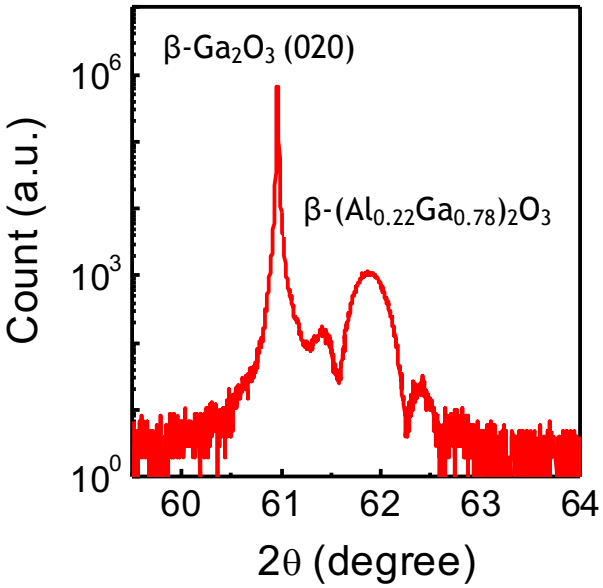
- Vertical MBE system (Riber M7) – O Plasma PAMBE
- Sources:
  - O plasma (unibulb), Ga, Si, Al, Fe

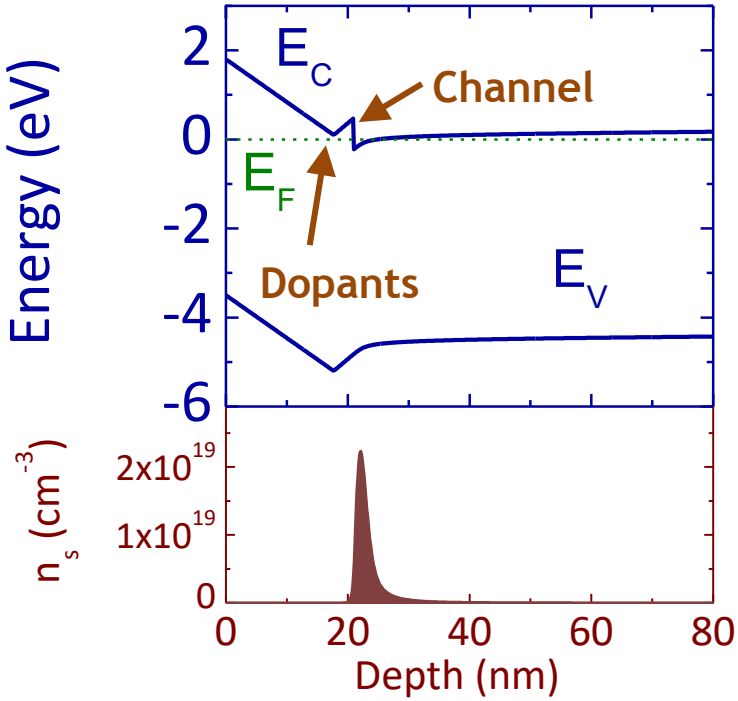
$(AlGa)_2O_3$/ Ga_2O_3 MODFETs







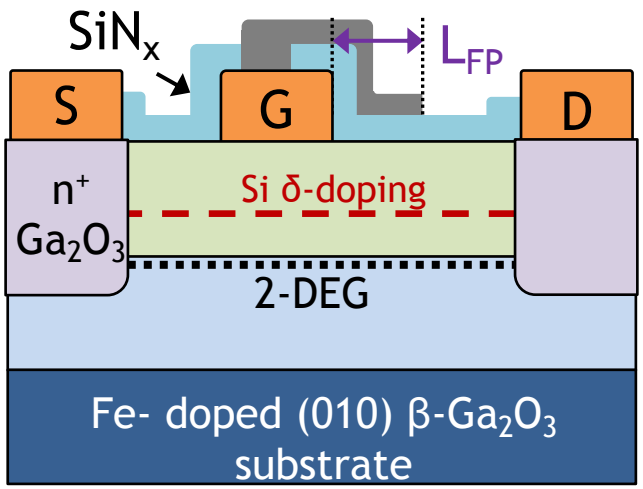


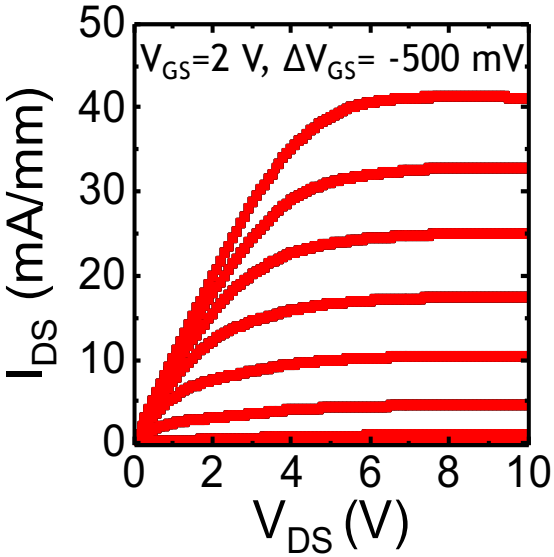


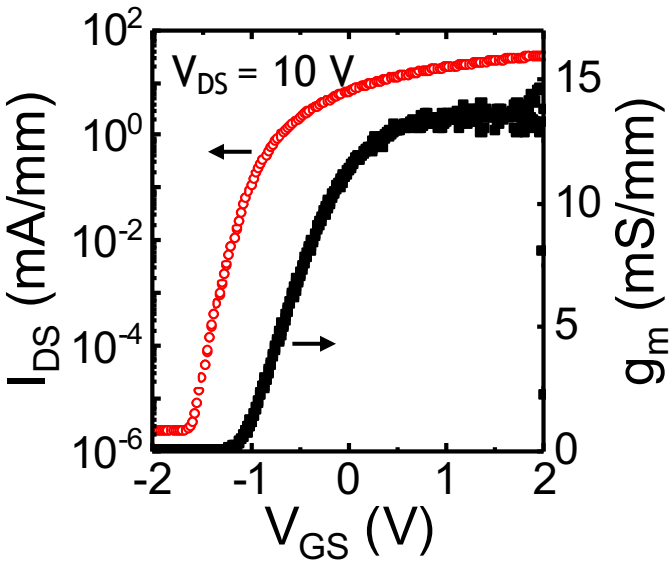
- Dopants spatially separated from channel
  - Eliminate ionized impurity scattering
    - Enhanced mobility
- Thickness confirmed from STEM
- Al composition (22%) from HRXRD

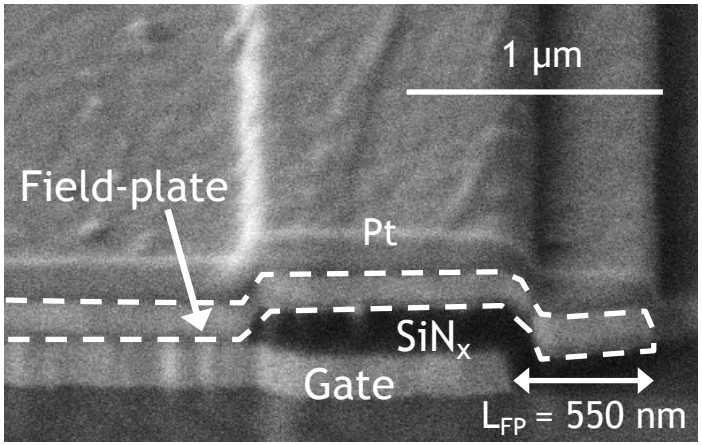
Sriram et al., APL 2017, Joishi et al., IEEE EDL, 2019

$(AlGa)_2O_3$/ Ga_2O_3 MODFET: Field plate engineering





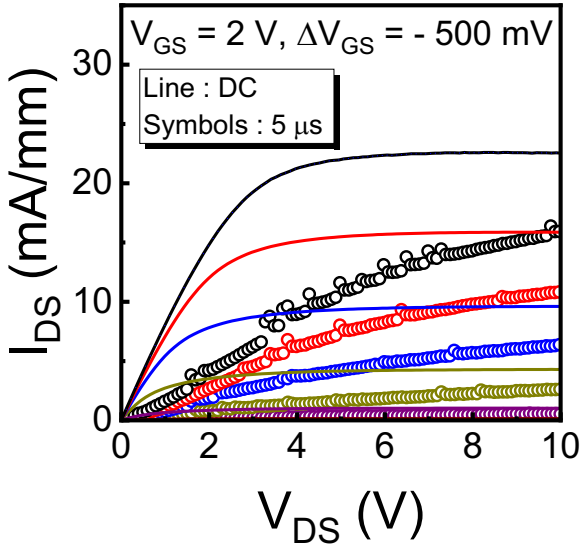


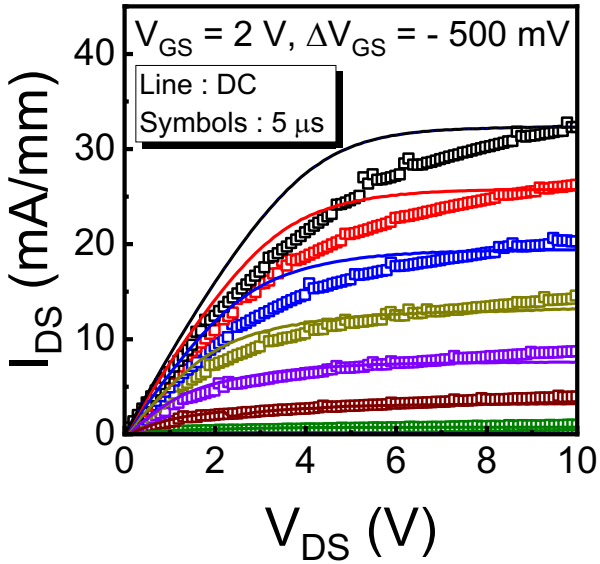


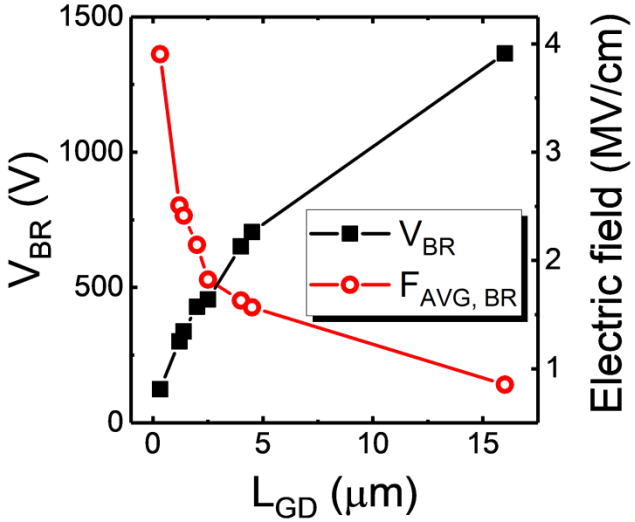
- To engineer peak field at the gate-drain edge
- SiN_x as the passivation dielectric (140 nm)
- Hall mobility
  - Room T: 101 cm^2/Vs @ $3.4X10^{12}$ cm^{-2}
- Device parameters (L_{SD} = 2 μm)
  - $I_{D,\ max}$ = 42 mA/mm
  - V_P = -1.2 V
  - I_{ON}/I_{OFF} = 10^7

Joishi et al., IEEE EDL, 2019

$(AlGa)_2O_3$/ Ga_2O_3 MODFET: device characteristics







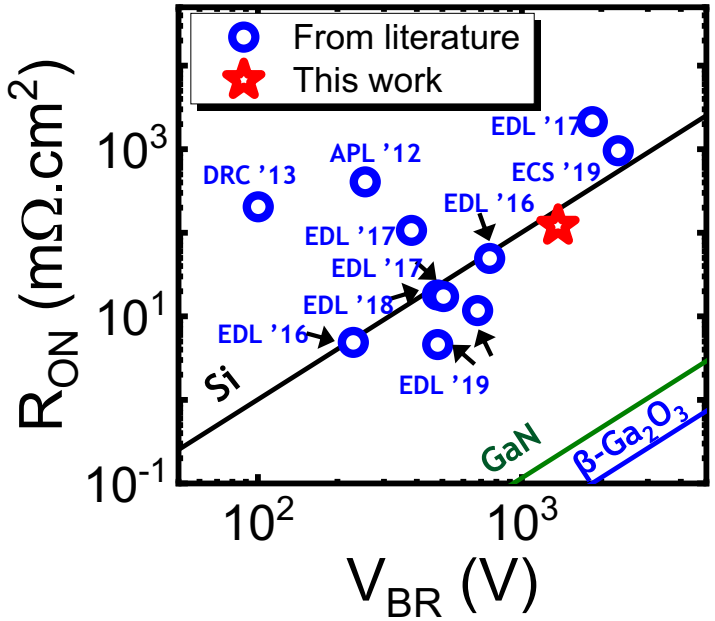
- **Pulsed IV**
  - **SiN_x passivation: improved knee-walkout**

Breakdown measurements

- Device in off-state
- For L_{GD} = 250 nm, F_{AVG} = 3.9 MV/cm
- For L_{GD} = 16 μm, V_{BR} = 1370 V
- Schottky gate limited breakdown

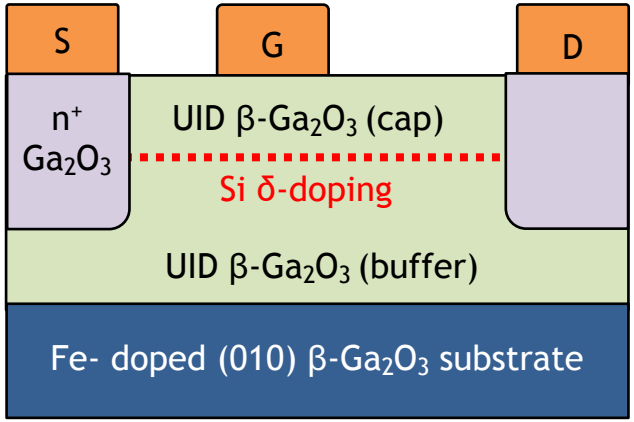
R_{ON}-V_{BR} benchmarking

- Data far-off from intrinsic limit.

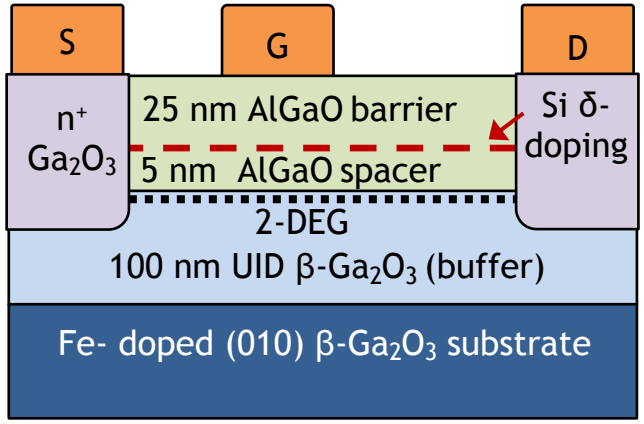


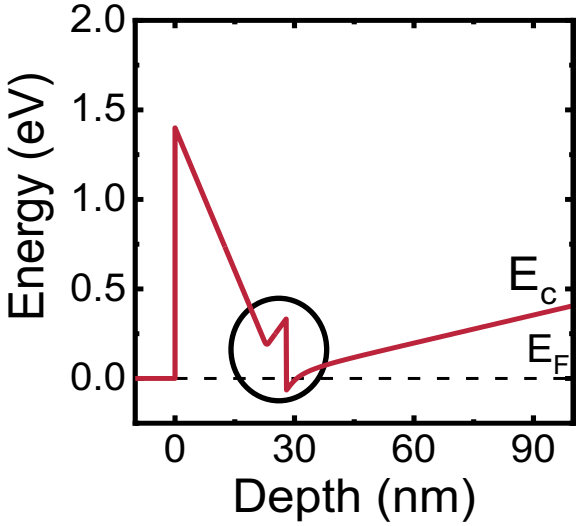
Increasing channel charge density

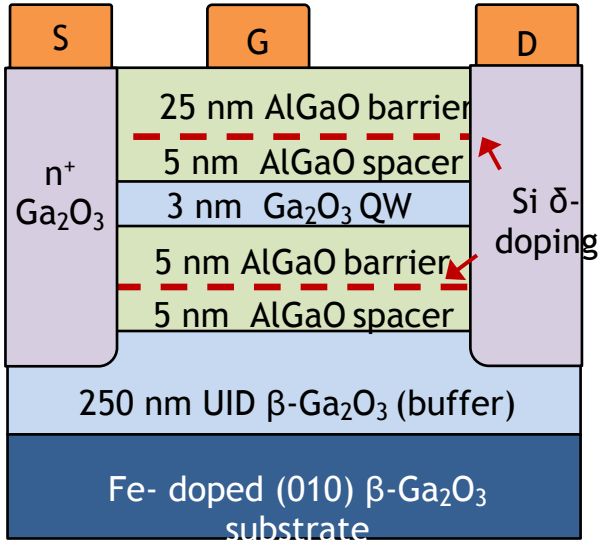
- Designs to increase charge density
- **Modulation doped FETs**
  - Increase the conduction band offset
    - Increasing the Al percentage
      - Bottleneck: epilayer growth
- **Quantum well MODFETs**
  - Multiple channels:
    - Secluded 2-DEG: growth challenge ?
- **Delta doped MESFETs**



Delta doped MESFETs







Multiple channel MODFETs

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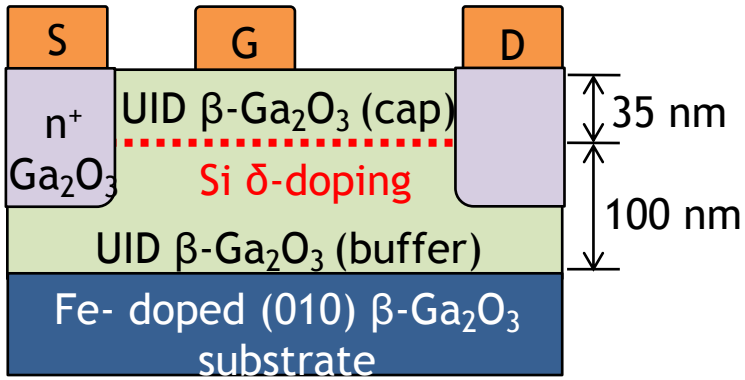
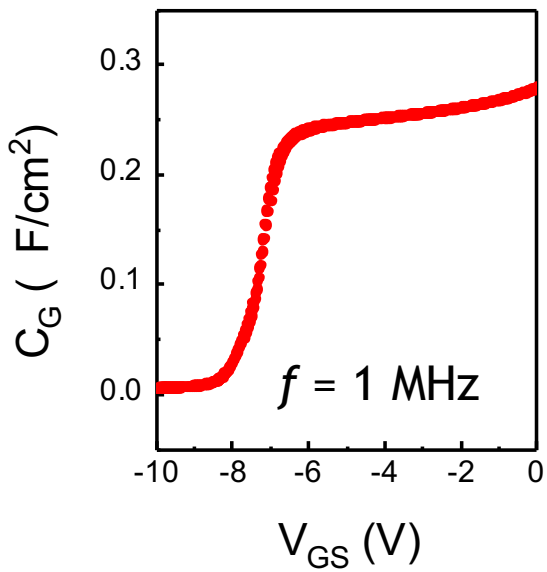
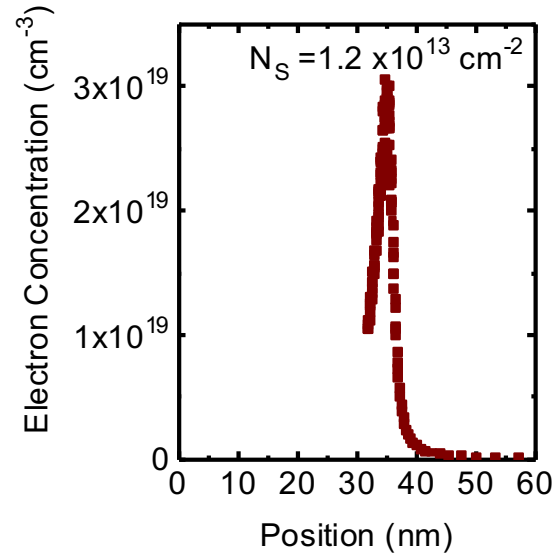
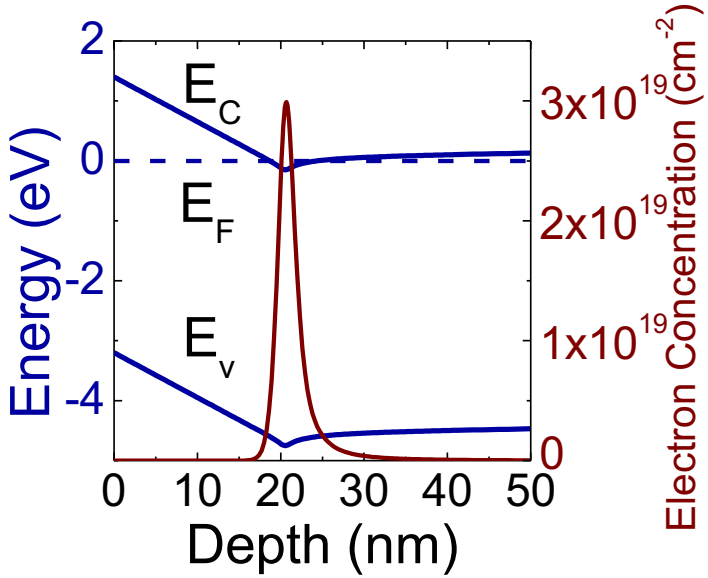
β- Ga_2O_3 delta doped MESFET





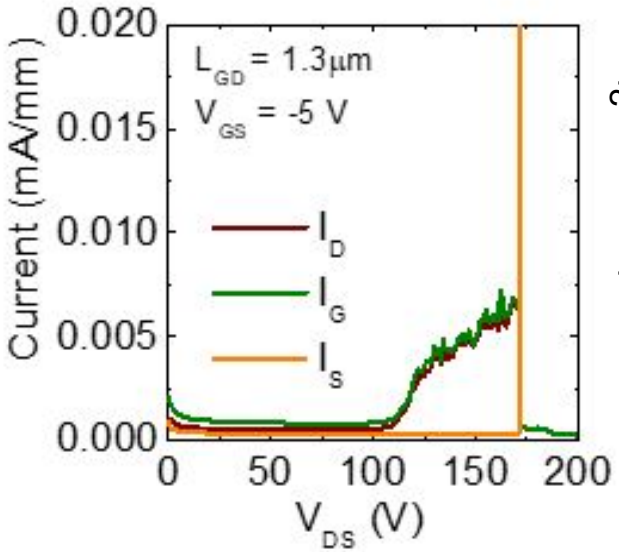


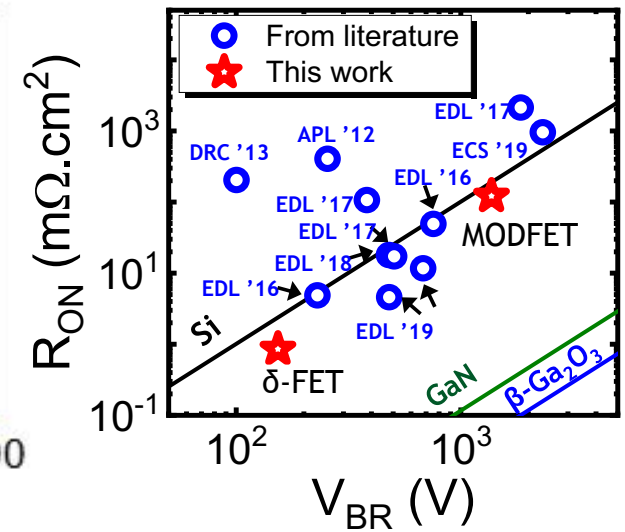


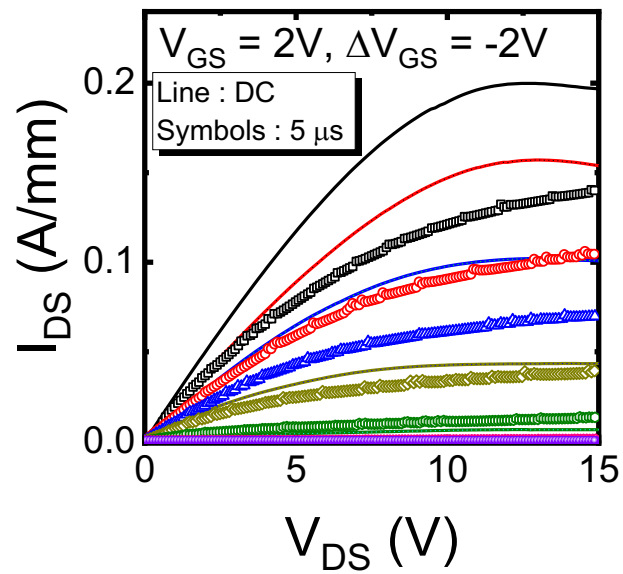
Zhanbo et al., EDL 2018

- High concentration of 2-DEG
- Enables scaling of gate-channel distance
- High gate breakdown voltage
- For similar doping density
  - Higher mobility than uniformly doped films
- Flat C-V characteristics
  - 2-DEG profile: (1.2×10^{13} cm^{-2} charge density)

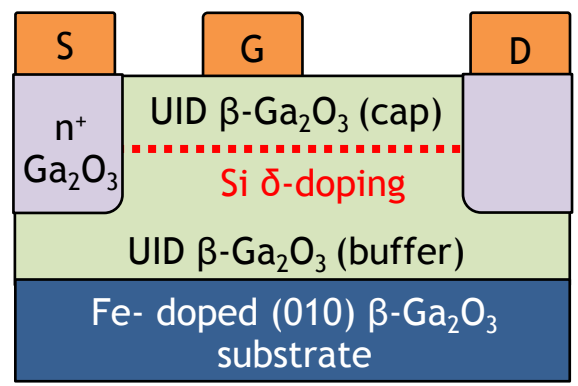
β- Ga_2O_3 delta doped MESFET



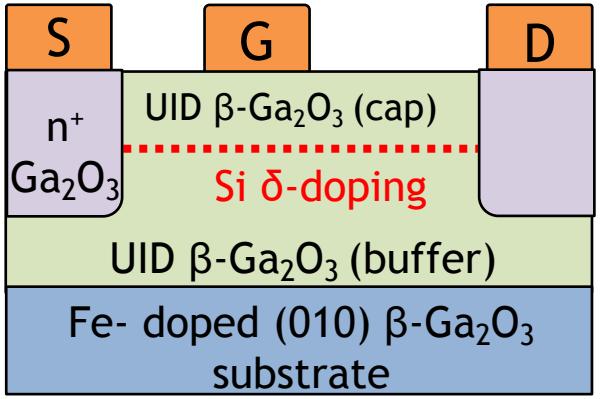




- Breakdown characteristics
- V_{BR} = 175 V, L_{GD} = 1.3 um, F_{AVG} = 1.3 MV/cm
  - R_{ON} better than single channel MODFETs
  - Field management design
- Dispersion characteristics
  - Significant knee-walkout
    - Source ?

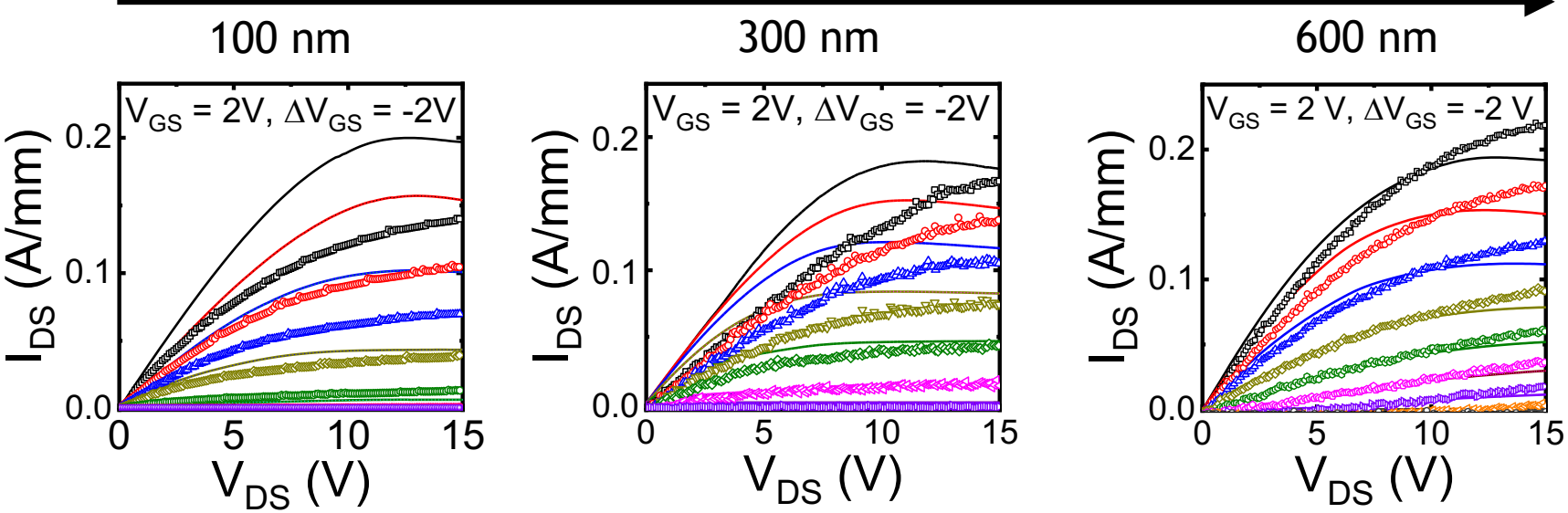


Source of dispersion: Fe doped substrate



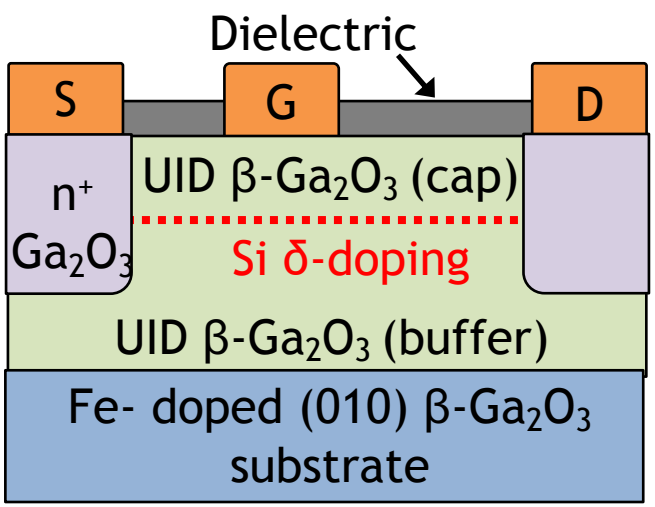
- **Dispersion characteristics**
  - **Thicker buffer FET**
    - Reduced dispersion
    - Lower R_{ON} degradation
- **Fe a source of dispersion**

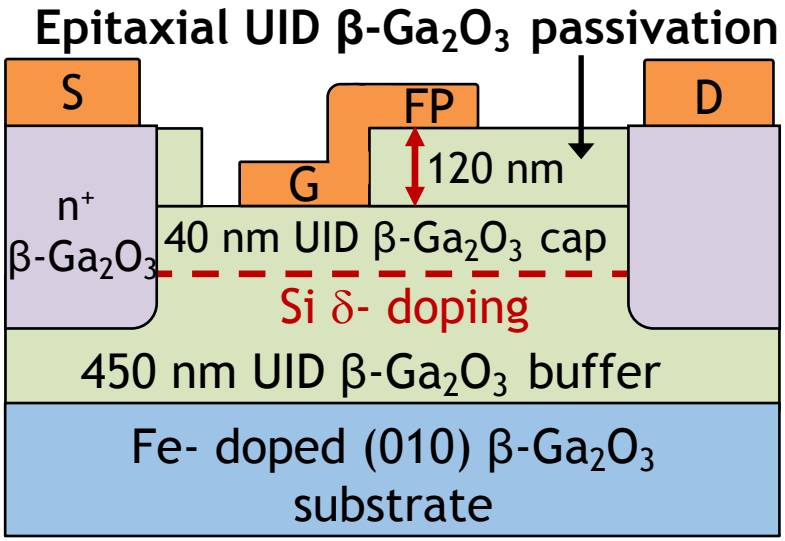
Buffer thickness



Lines: DC, Symbols: Pulsed

Epitaxial passivation: β-Ga_2O_3 delta doped MESFET



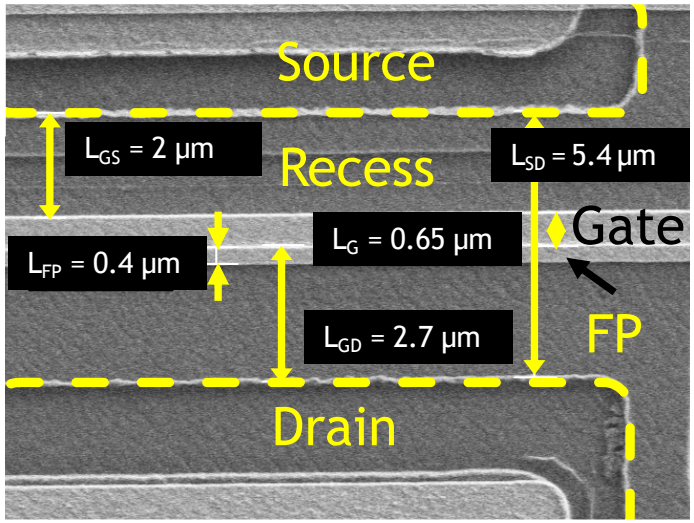


Ex situ passivation

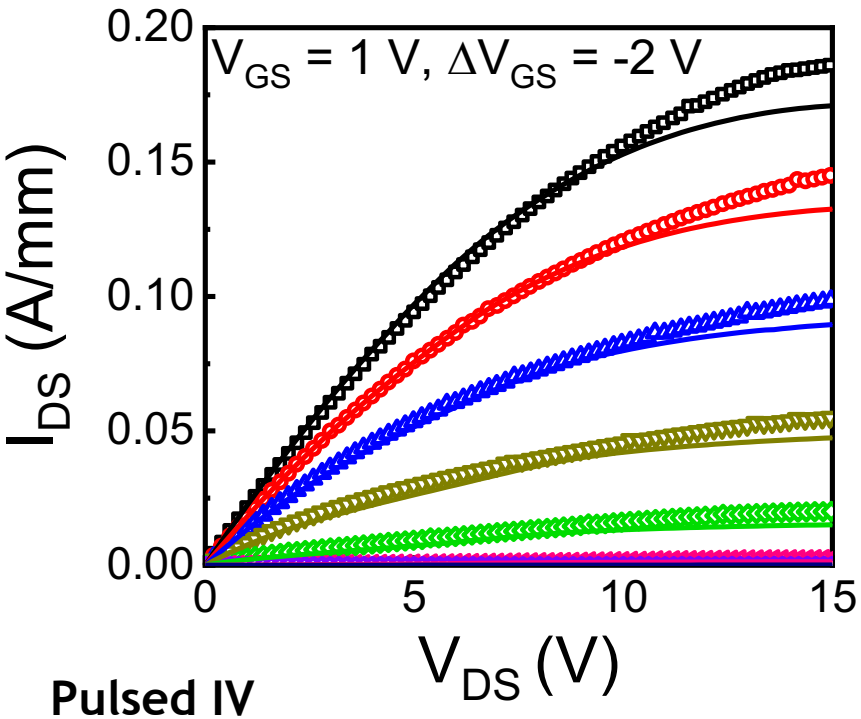
- Non-ideal dielectric/β-Ga_2O_3 interface

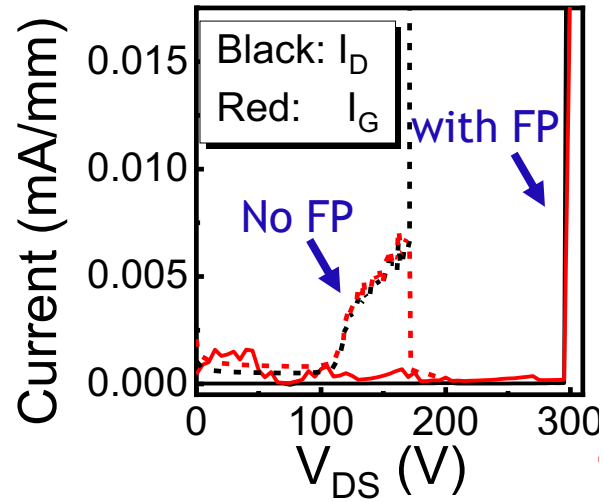
Epitaxial passivation

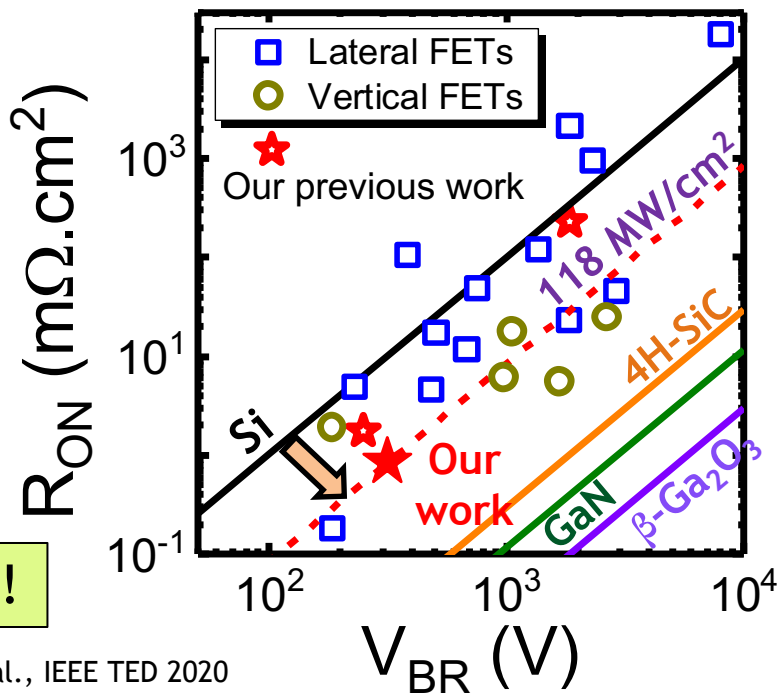
- Semiconductor-dielectric interface absent
  - No interface exposure to high fields
  - Ex situ surface far off from the 2-DEG
  - **Better dispersion properties**
- High dielectric constant of β-Ga_2O_3
  - **Better breakdown characteristics**



Transistor characteristics







Pulsed IV

- Better dispersion characteristics

Breakdown characteristics

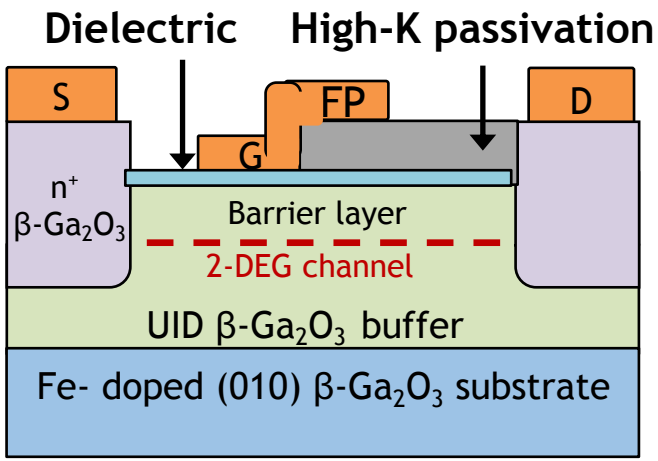
- V_{BR} = 315 V, F_{AVG} = 2.3 MV/cm
- R_{ON} vs V_{BR} benchmarking

Further device engineering needed!

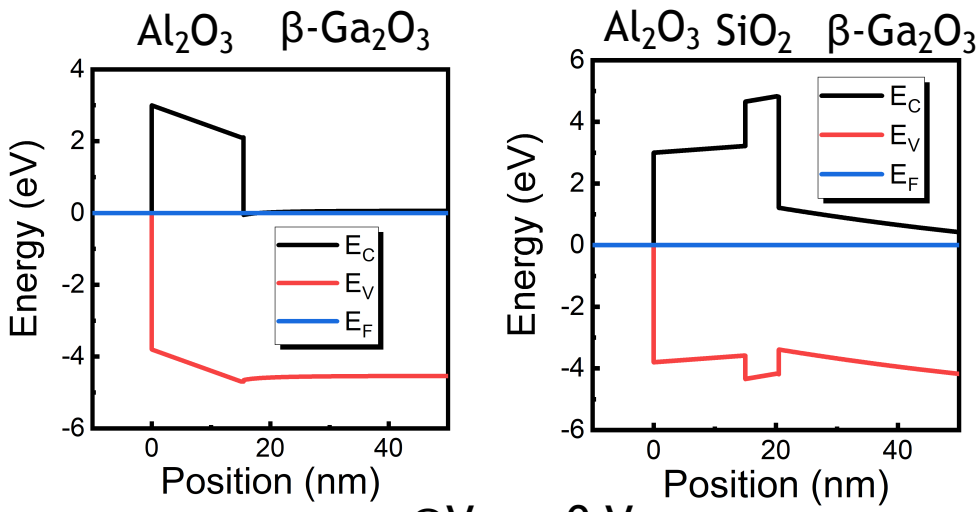
Joishi et al., IEEE TED 2020

Device engineering: towards enhancement mode transistors

- **Channel charge density > 1.5×10^{13} cm^{-2}:** Significant gate leakage
- **Need for dielectrics**
- **Conventional dielectric for β-Ga_2O_3: Al_2O_3**
  - High dielectric constant
  - Positive fixed oxide charge (N_{OX})
  - D-mode operation
    - High channel charge density pinch-off



- **SiO_2 as a dielectric on Ga_2O_3**
  - Highest known ΔE_c till date
    - Reduced gate leakage
  - Negative N_{OX}
    - E-mode operation ✓
- **Bilayer dielectric (Al_2O_3/SiO_2)**
  - Leverage the combined benefits of SiO_2 and Al_2O_3



@V_{GS} = 0 V

Outline

- β-Ga_2O_3: Background and motivation
- Device fabrication/characterization
  - Modulation doped FETs
  - Delta doped MESFETs
  - Enhancement-mode MOS Capacitors
- High-k/bilayer dielectric field management
- Conclusions

ALD growth of dielectrics (IITB)

SiO_2

- Tris(dimethylamino)silane
- O_2 plasma: 300 W
- Temperature: 250 ^oC

Al_2O_3

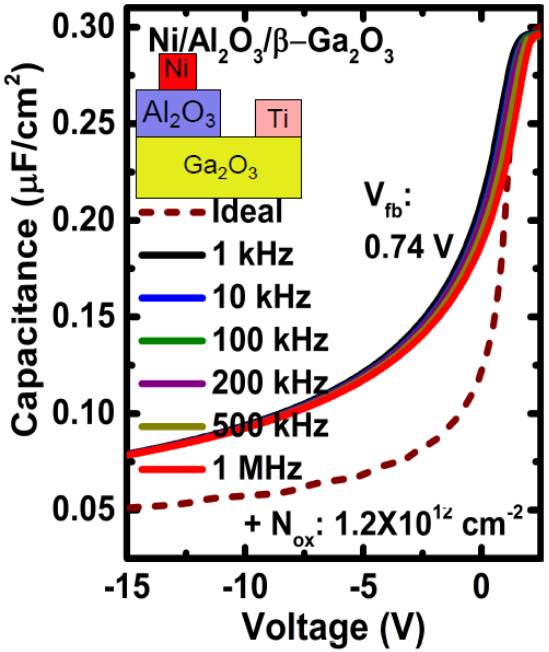
- Trimethyl aluminum (TMA)
- Thermal (DI water)
- Temperature: 250 ^oC

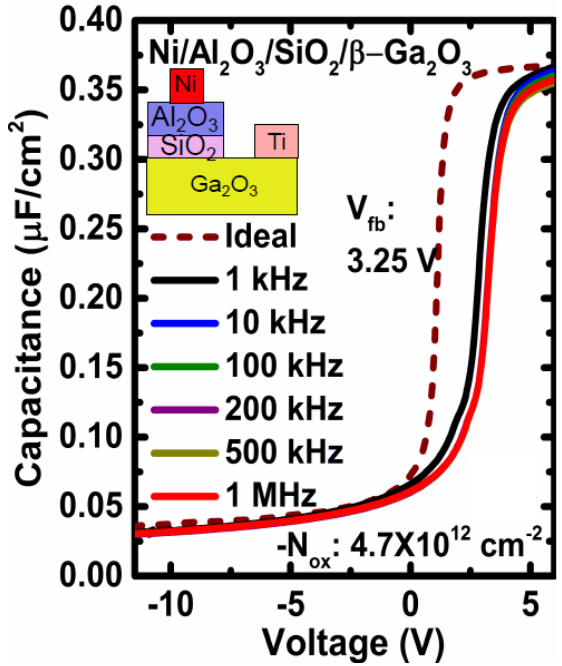
AlN

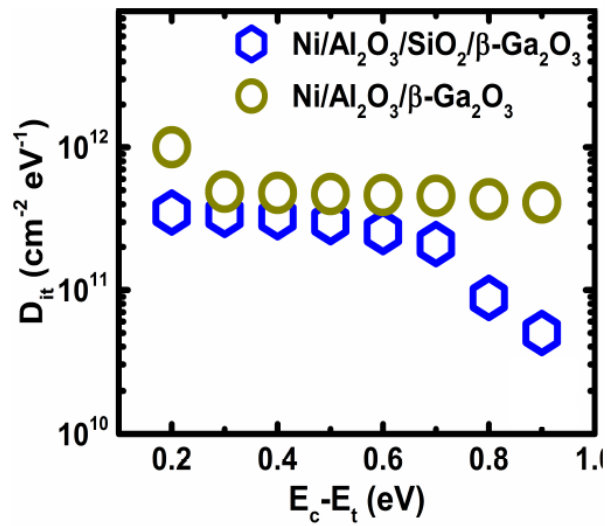
- Trimethyl aluminum (TMA)
- NH_3 plasma: 300 W
- Temperature: 200 ^oC

- **Cambridge Nanotech Fiji 200 ALD system**
- **Plasma sources: O_2, N_2, NH_3**
- **Depositions (Plasma/Thermal)**
  - SiO_2, Al_2O_3, HfO_2, ZrO_2, AlN, TiN, TiO_2, Nb_2O_5

Device characteristics

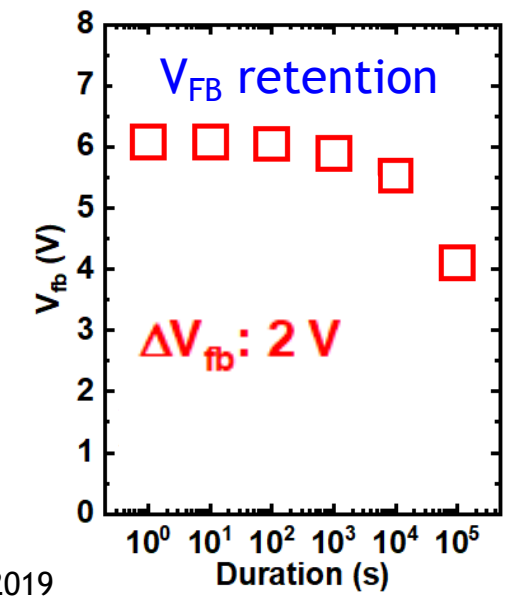






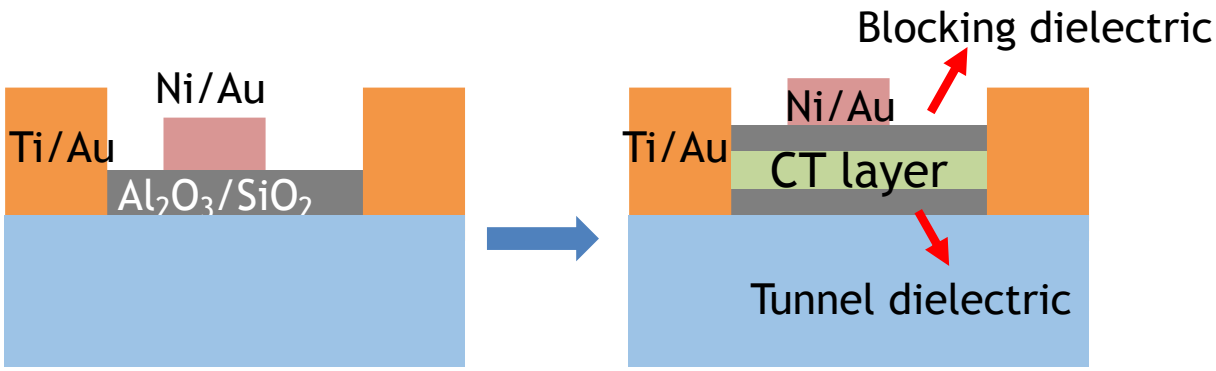
Al_2O_3 → Al_2O_3/SiO_2

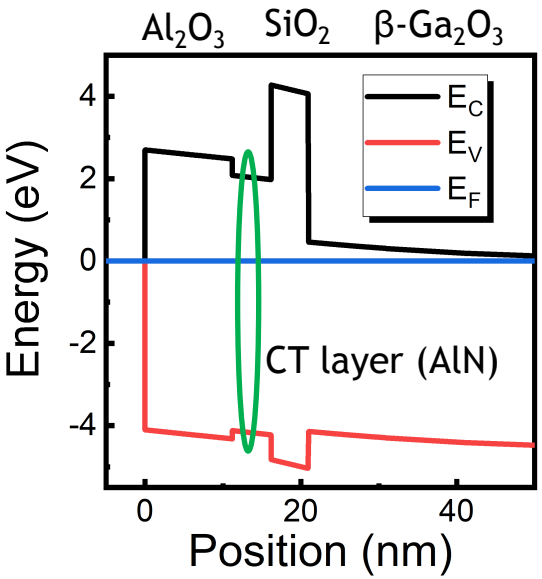
- **Total charge depleted**
  - **~1.6x10^{13} cm^{-2}**
- Steep depletion characteristics
  - Better interface, low D_{IT}
- **Negative N_{OX}: normally-OFF operation**
  - **Poor V_{FB} retention**



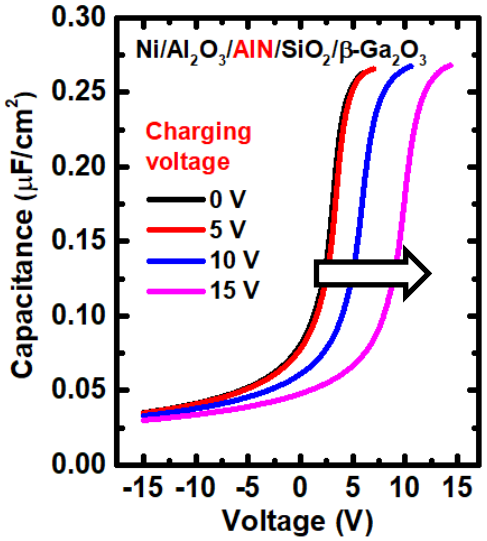
Dipankar et al., APL 2019

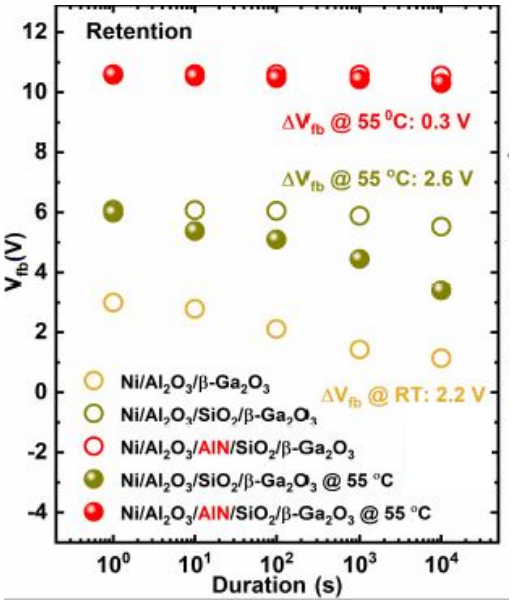
Charge trap layer





- **To engineer negative N_{OX} for e-mode operation**
  - **Addition of a charge trap (C.T) layer**
- **Non-polarized AlN as a CT layer**
  - V_{FB} domain
    - [3.5 V, 10 V]
  - Charge depleted
    - 1.5×10^{13} cm^{-2}
  - Excellent charge retention
    - @ RT and 55 °C





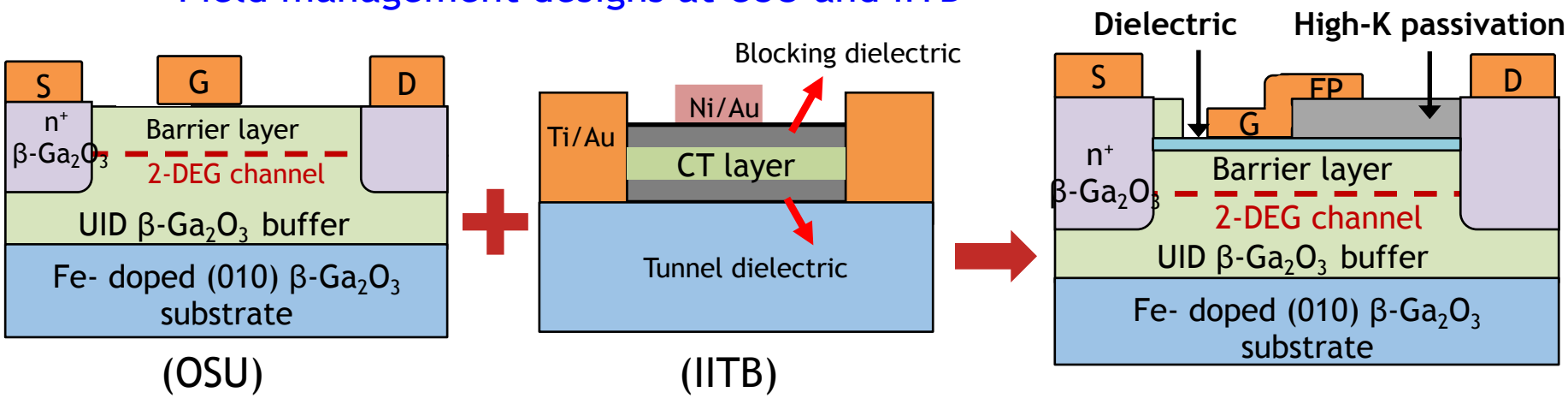
Dipankar et al., APL 2020

Conclusions

- Ga_2O_3 for power electronics
  - Melt-based growth: cost factor?
- FoM's for Ga_2O_3: shows promise but are simple guides
- ON-resistance vs field management in MODFETs and δ-FETs
- AlN as a charge trap layer for tunable V_T transistors

The future

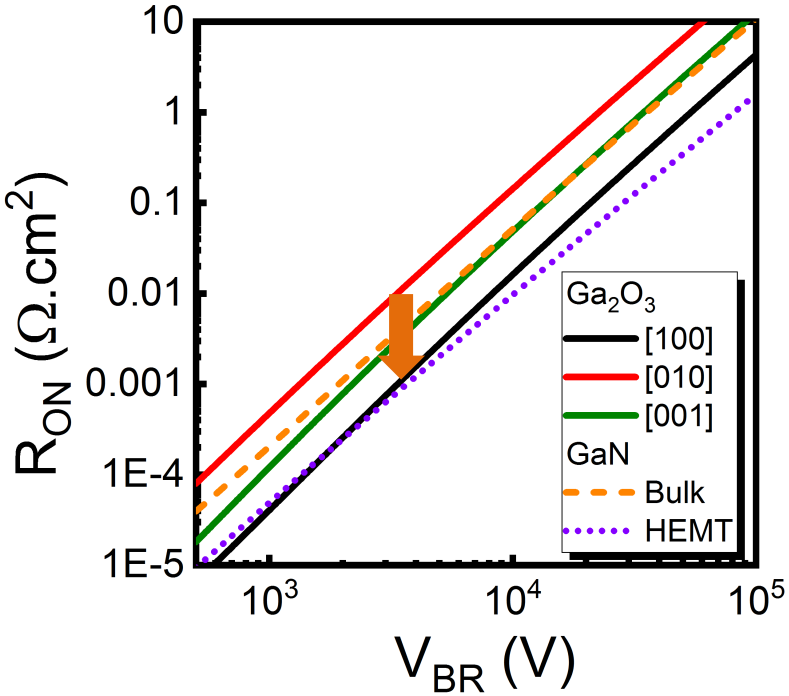
- Delta-doped FETs from OSU + AlN charge trap layer at IITB
  - Enhancement mode delta-doped FETs
- Development of high-K dielectric BZN at IITB
  - Field management designs at OSU and IITB

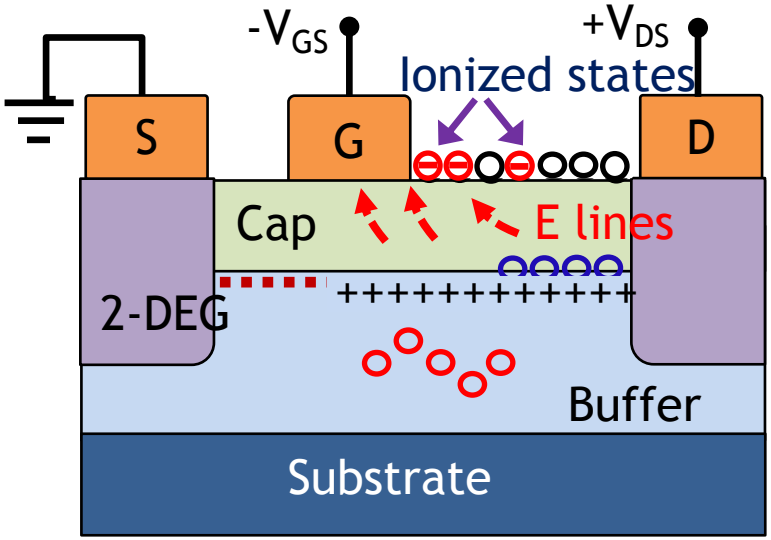


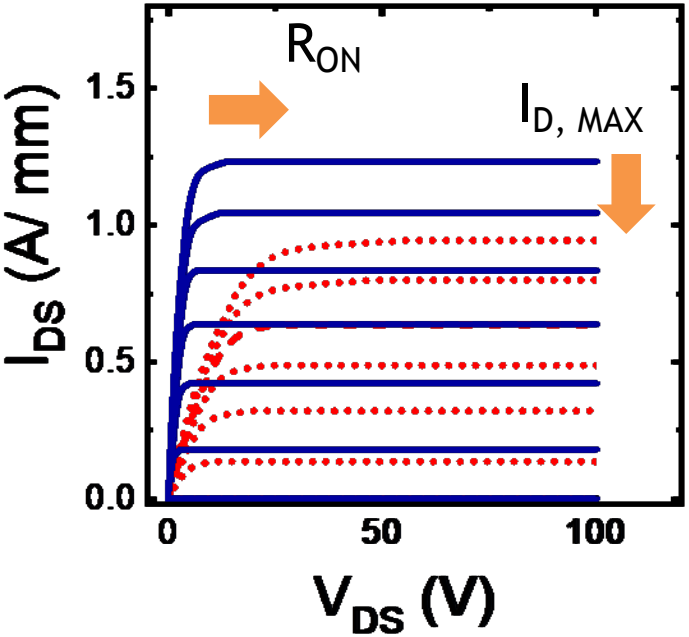
Thank you

Backup slides

Importance of carrier mobility

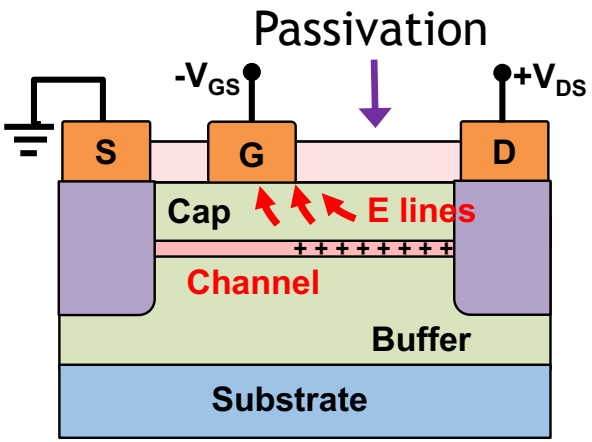


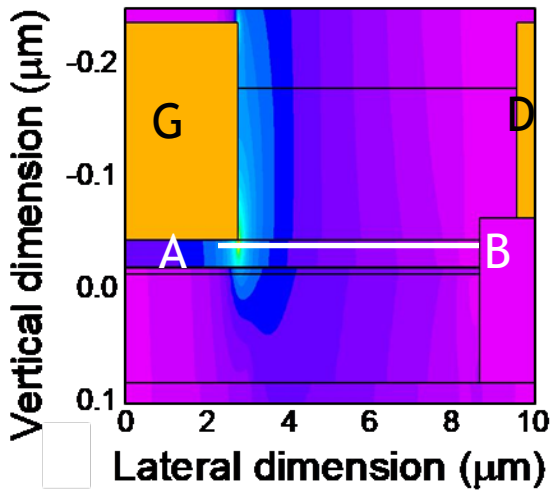


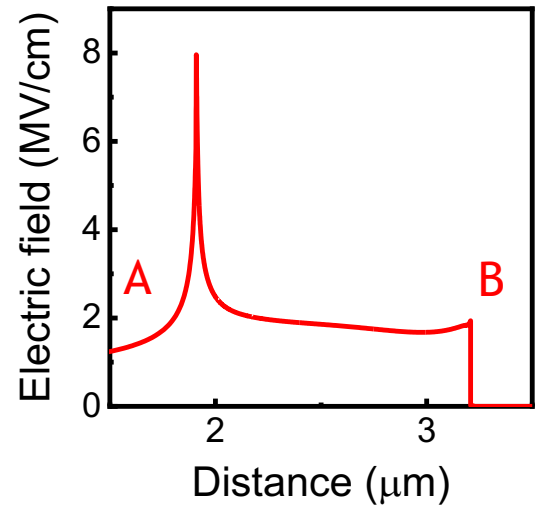


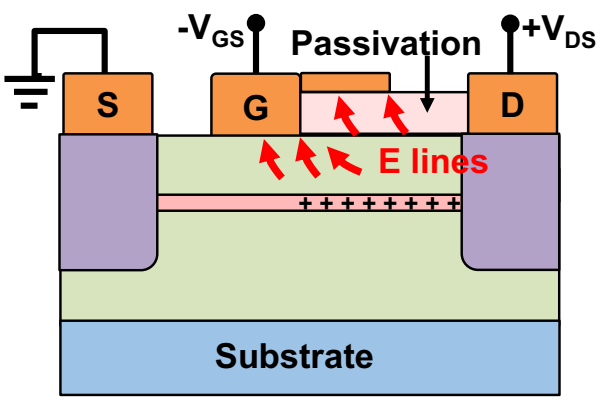
- **AlGaN/GaN HEMTs**
  - Lateral power devices
- **Ga_2O_3 heterojunction capability** ✓
- **Design Ga_2O_3 FETs that enable**
  - High mobility **x** charge density.
- **Lateral power devices**
  - Degradation in R_{ON} => dynamic R_{ON}

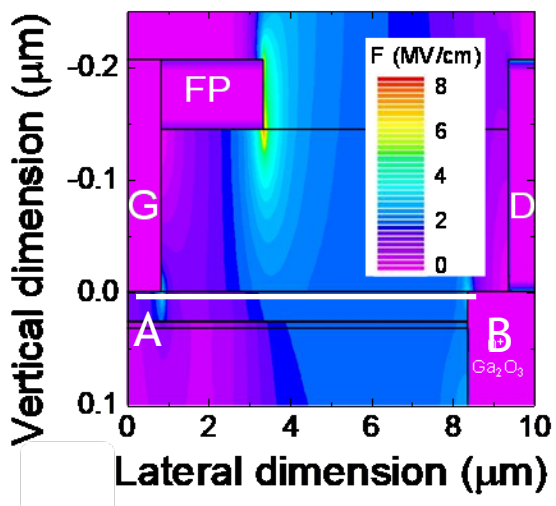
Motivation: breakdown field management

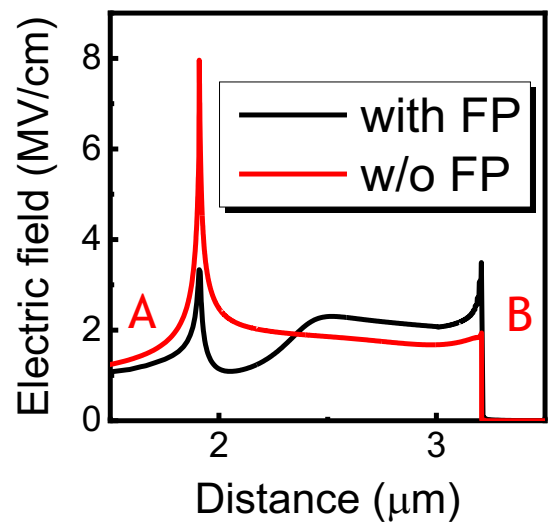






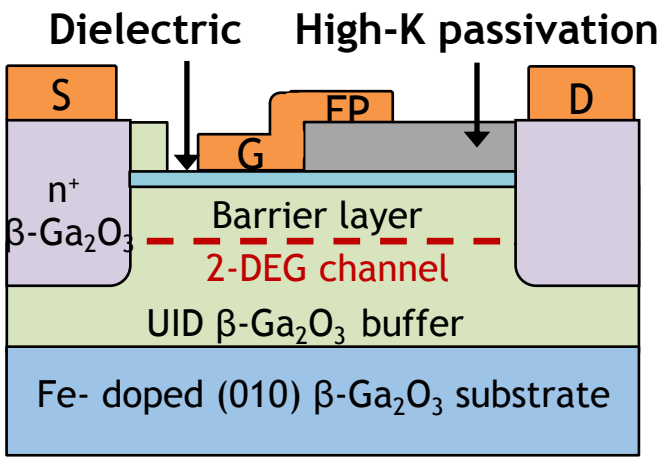




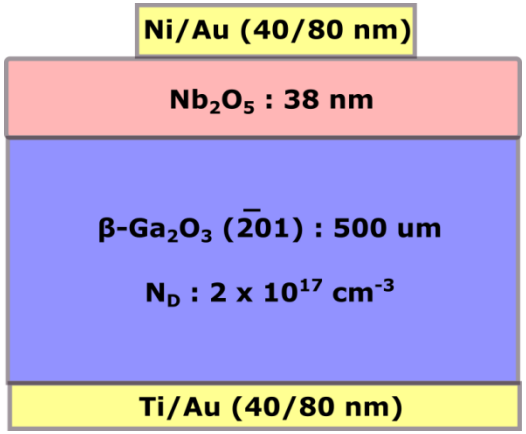


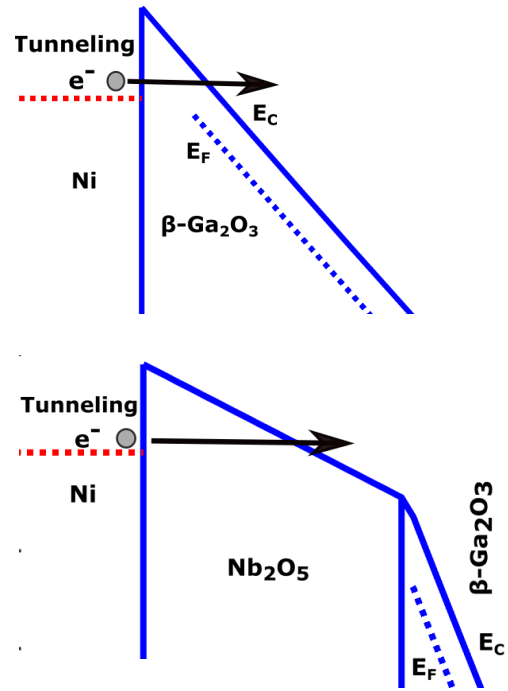
- Field-plate (FP): additional electrode for E lines termination
- **Power switching: Surface passivation, field-plate, e-mode operation**

Field engineering: High-K dielectrics

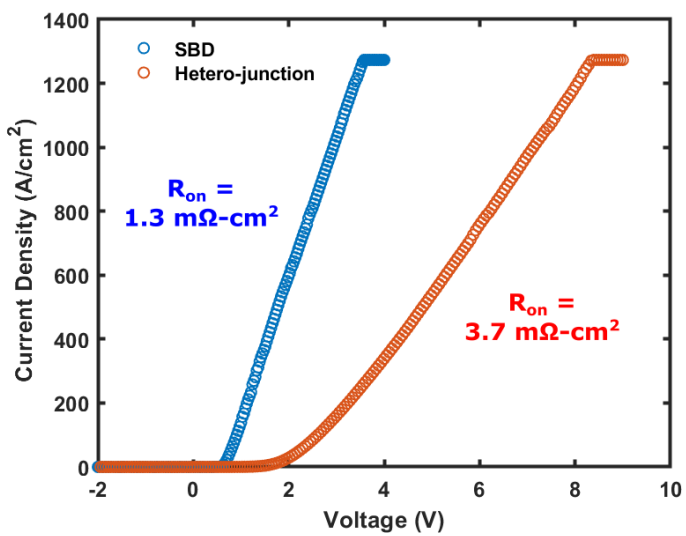


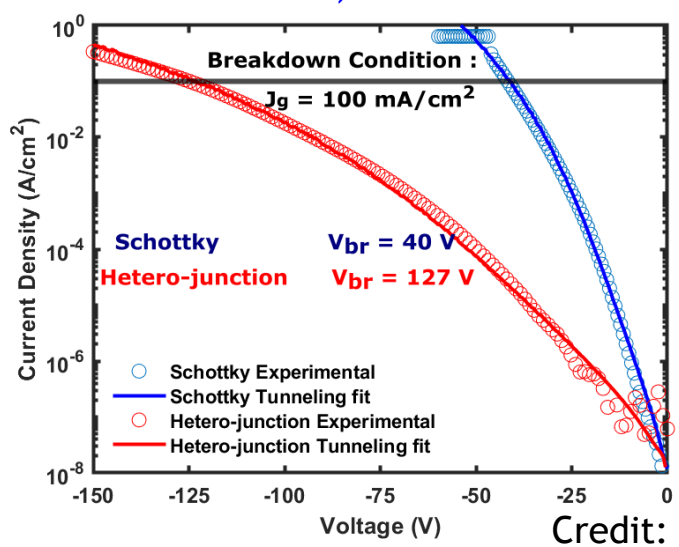
Ref: Zhanbo et al., APL 2019





- **High-K dielectric to reduce peak field at the gate edge.**
  - MIS diodes using Nb_2O_5 (dielectric constant = 50)

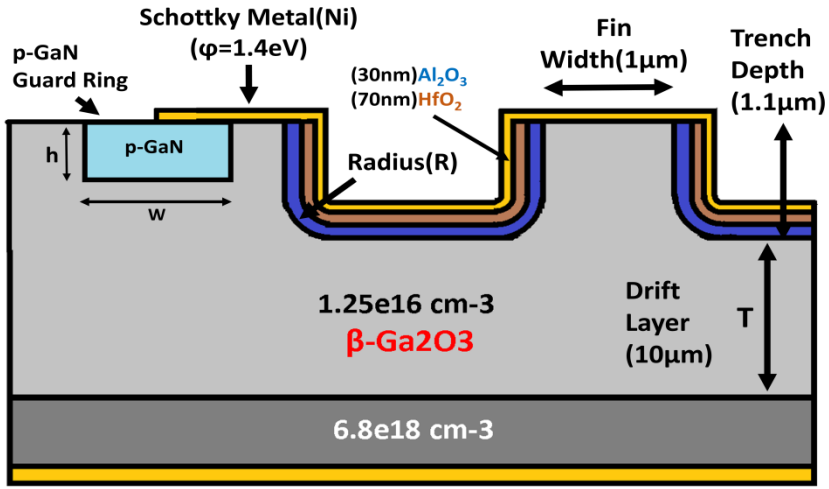


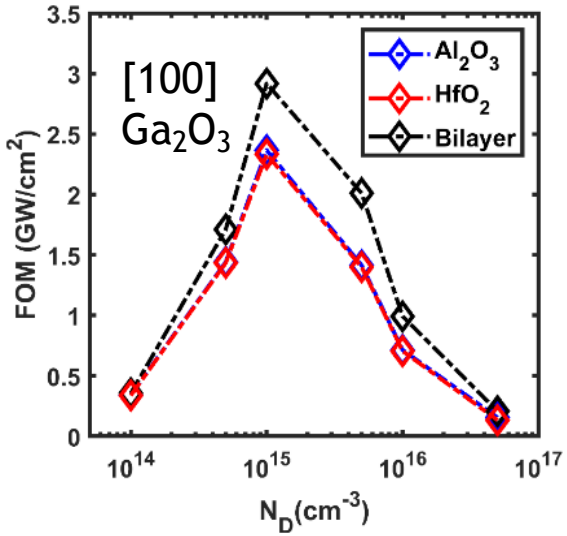


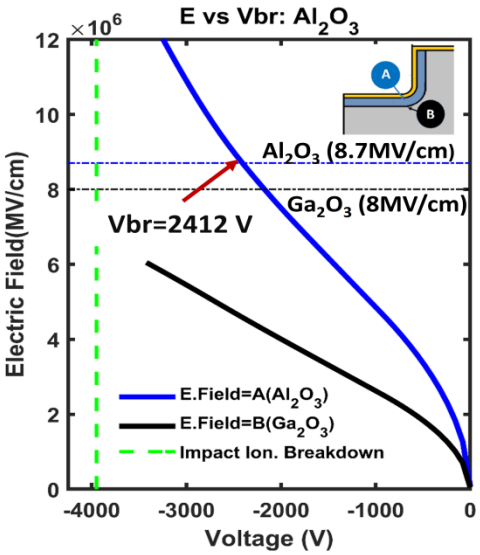
Credit: Prabhans, Jayeeta

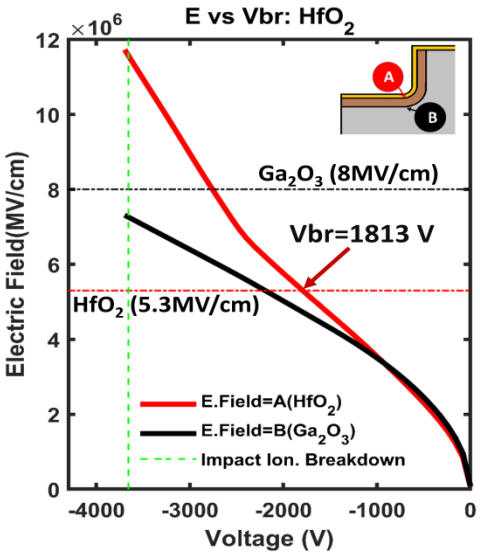
Vertical topology: field management using bilayer dielectrics

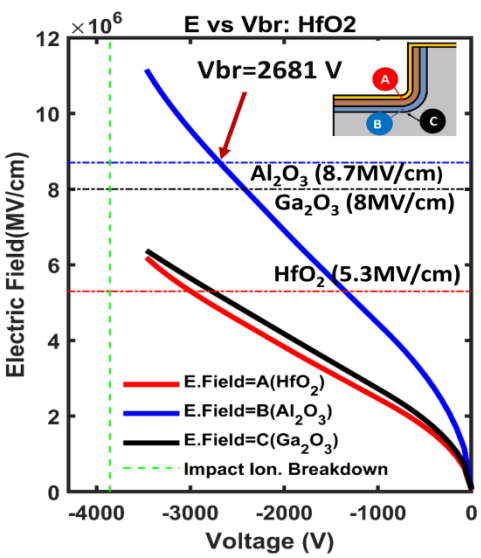
- **Leveraging the combined benefits of a high-K/ low-K dielectric combination**











Credit: Ravikiran