PWR SOC 12
Integrated Power Conversion and Power Management
next generation technology for emerging business opportunities
new technologies new applications new markets

Device Technology for GaN-based Integrated Power Electronics

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Outline

- GaN's benefits for power electronics
- Technology challenges and solutions
  - Discrete power transistors
  - Integration of power switches and rectifiers
  - Smart power ICs
- Summary

Trends in Power Converters

- **High voltage**, large capacity, **high frequency**
- Compact size, smart control and low-cost
- **High-temperature** operation and low-cost cooling systems

New semiconductor materials with fundamental advantages over Si: GaN and SiC

GaN Power Devices and ICs on Si

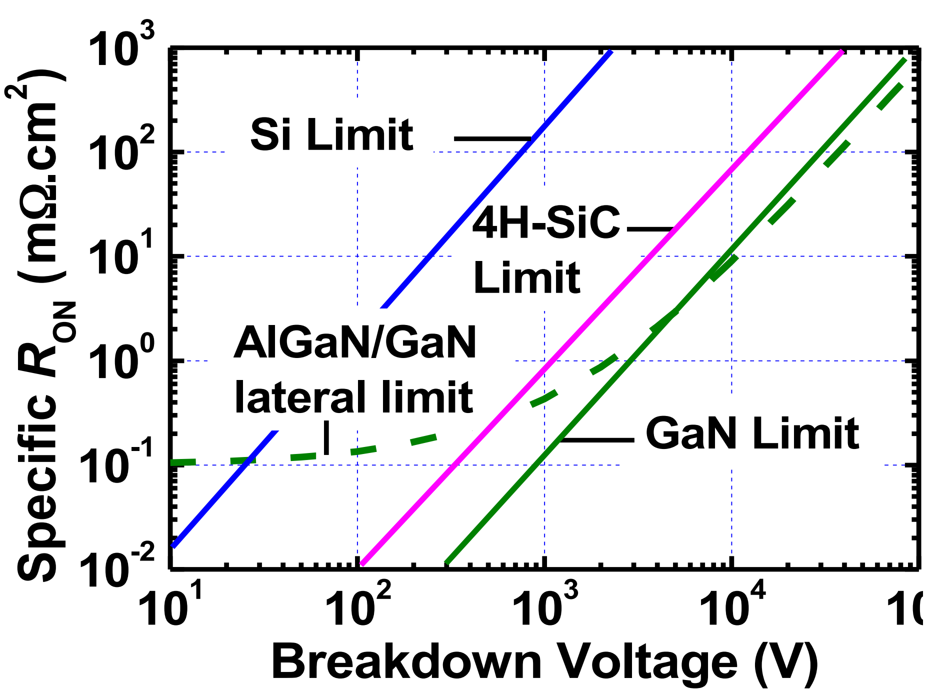
GaN: superior material properties

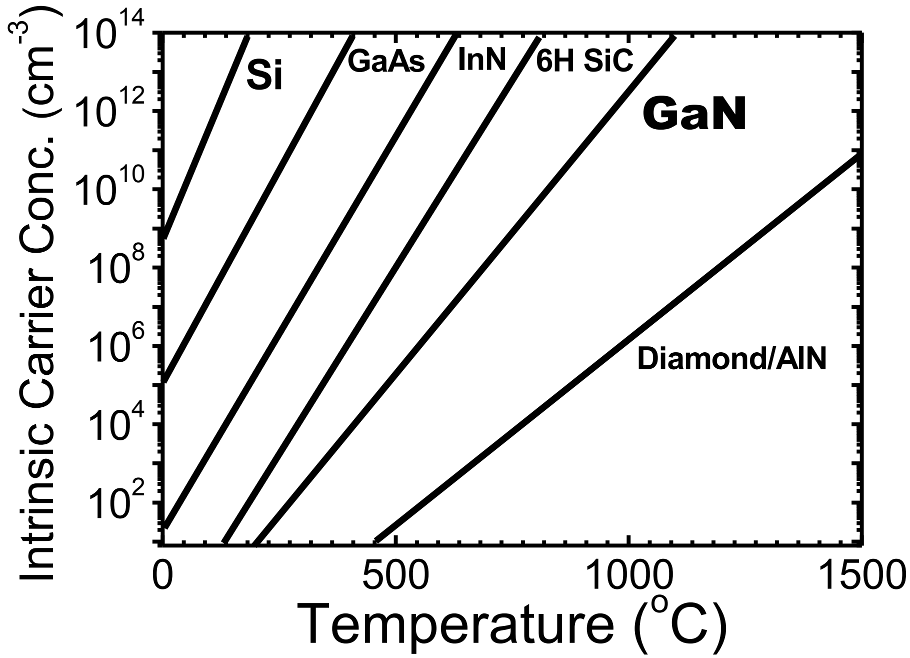
Physical Properties	(Si)	(GaAs)	(4H-SiC)	(GaN)
Bandgap (eV)	1.11	1.43	3.26	3.4
Thermal Cond. (W/cm·K)	1.5	0.46	3.5	1.5
Breakdown E-field (MV/cm)	0.3	0.3	2.5	2.5~3
e saturation velocity ($\times 10^7$cm/s)	1.0	2.0	2.0	2.5
e Mobility ($cm^2/V \cdot s$)	1300	5000 (2DEG)	600-900	2000 (2DEG)
BHFFOM* (μE_c^2)	1	9.5	45	98

*BHFFOM: Baliga's high frequency figure of merit

GaN for Power Electronics

Breaking the Si Limit





- **Lower loss, higher switching frequency, higher operating temperature**

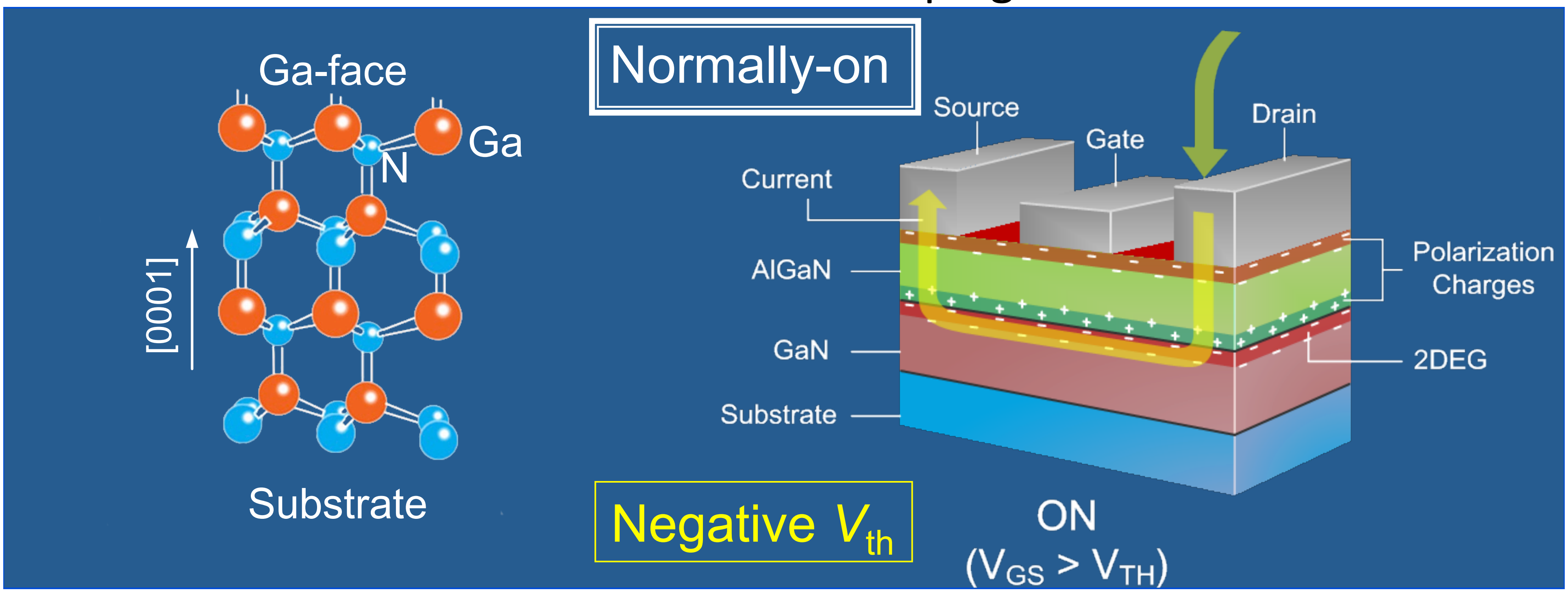
GaN and III-nitride: strong polarization

Charge Polarization

- Spontaneous
- Piezoelectric

Commercial AlGaN/GaN-on-Si wafers:

- *Ga-face*: Positive polarization charges at the AlGaN/GaN interface → high 2DEG density
- Normally-on 2DEG channel without any intentional doping

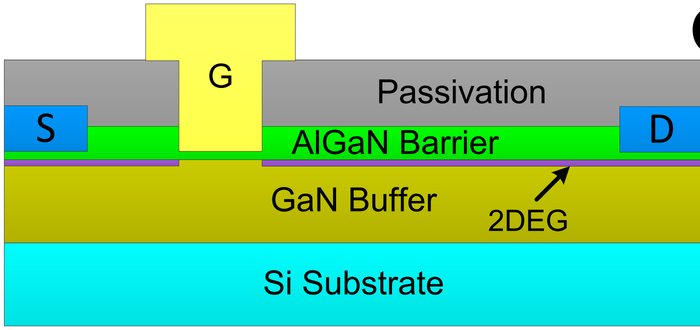


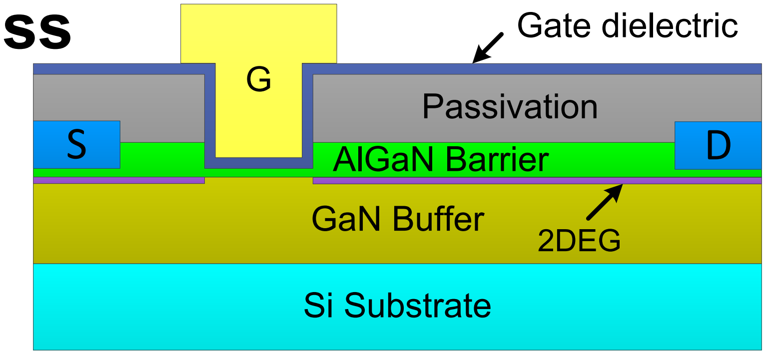
Challenges for lateral AlGaN/GaN power HEMTs

- **Gate control:** normally-off operation, low gate leakage and large gate swing
- **Surface passivation:** low current collapse and low dynamic R_{ON}
- **Buffer:** low "OFF" state leakage, low trap state density and stress compensation/release
- **Substrate:** (111) Si --- how to integrate with Si CMOS (on (100) Si)?

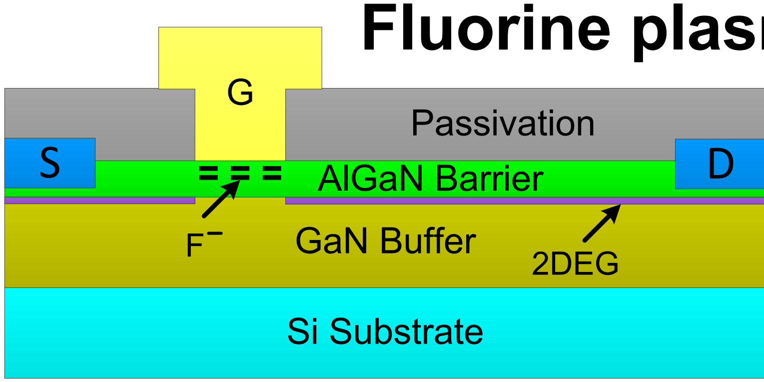
GaN normally-off transistor technologies

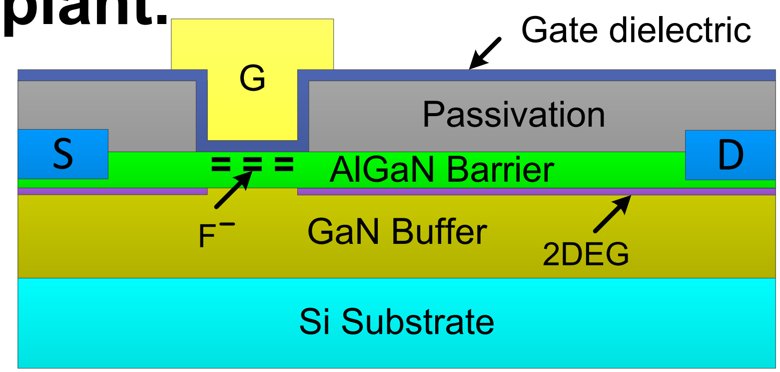
Gate recess





Fluorine plasma ion implant.

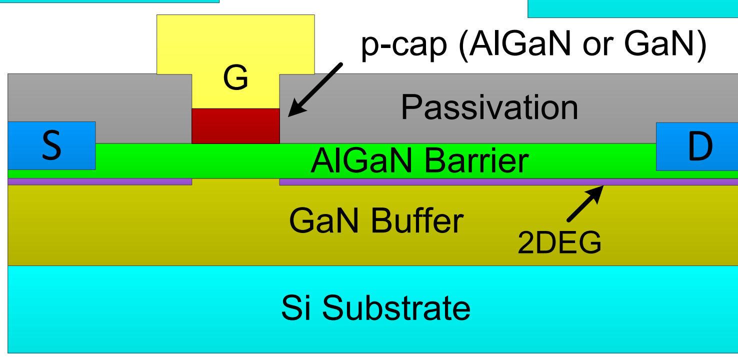




HEMT

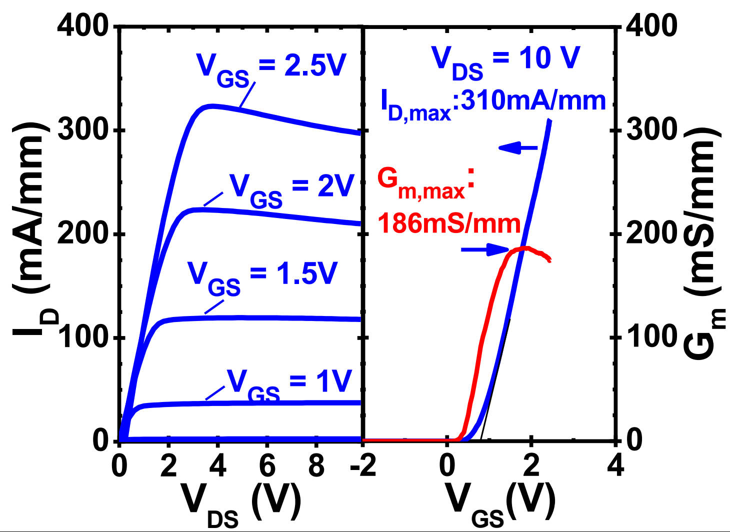
MIS-HEMT

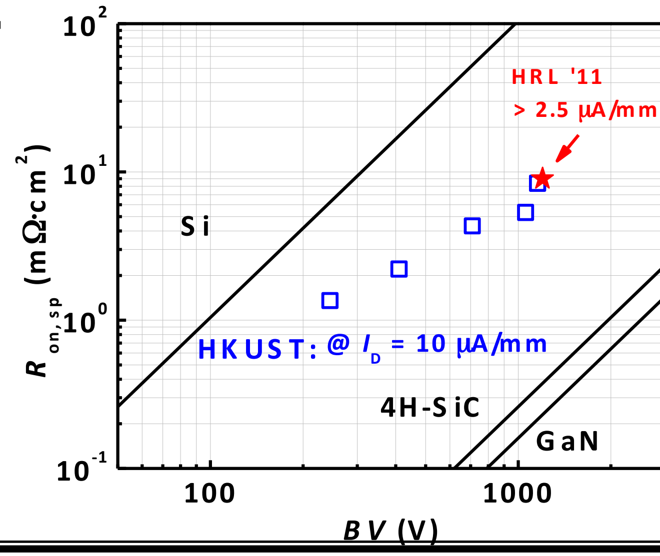
P-type cap



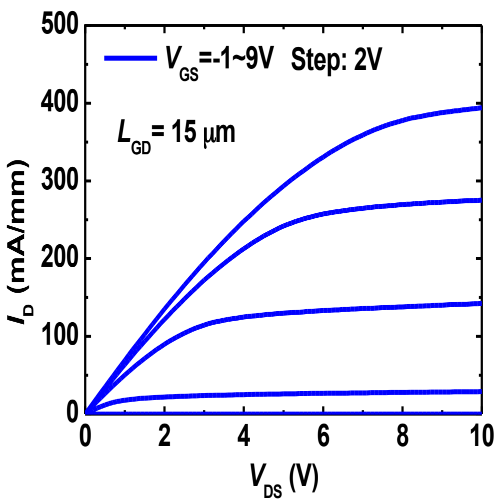
Normally-off transistor performance (by F implant)

HEMT

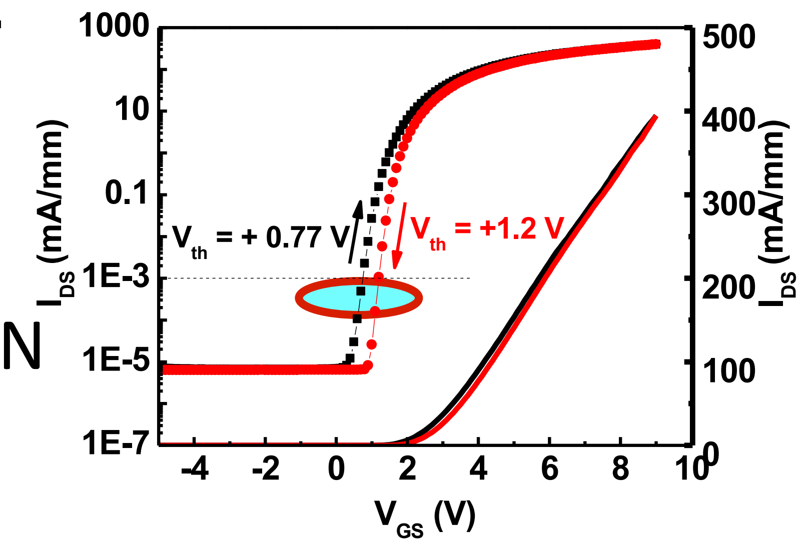




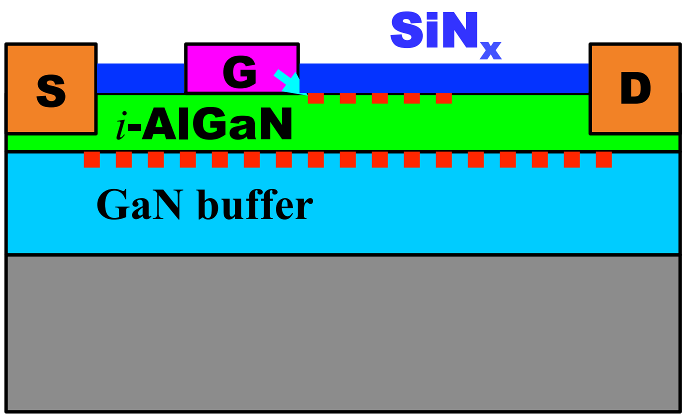
MIS-HEMT



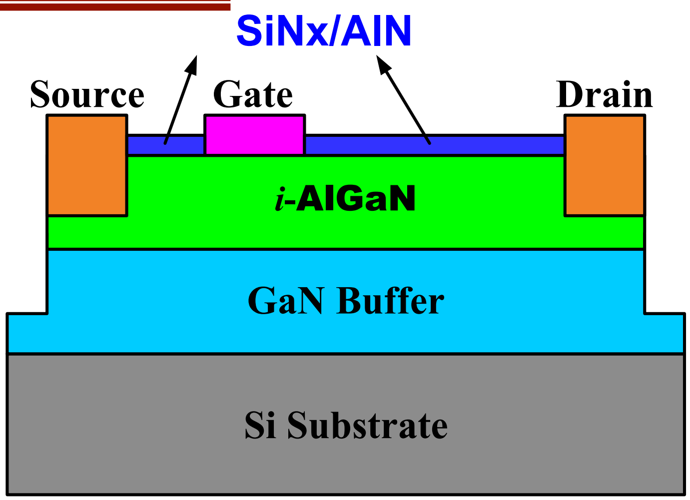
Hysteresis:
traps at the dielectric/(Al)GaN interface

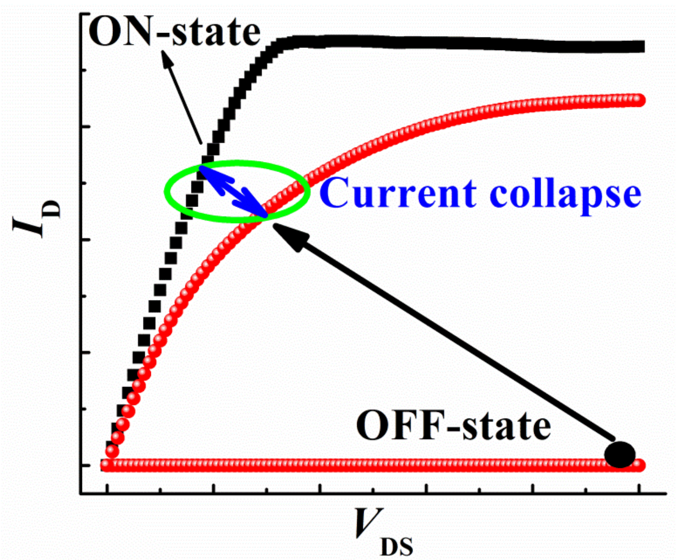


Surface passivation: current collapse reduction



AlGaN/GaN HEMT



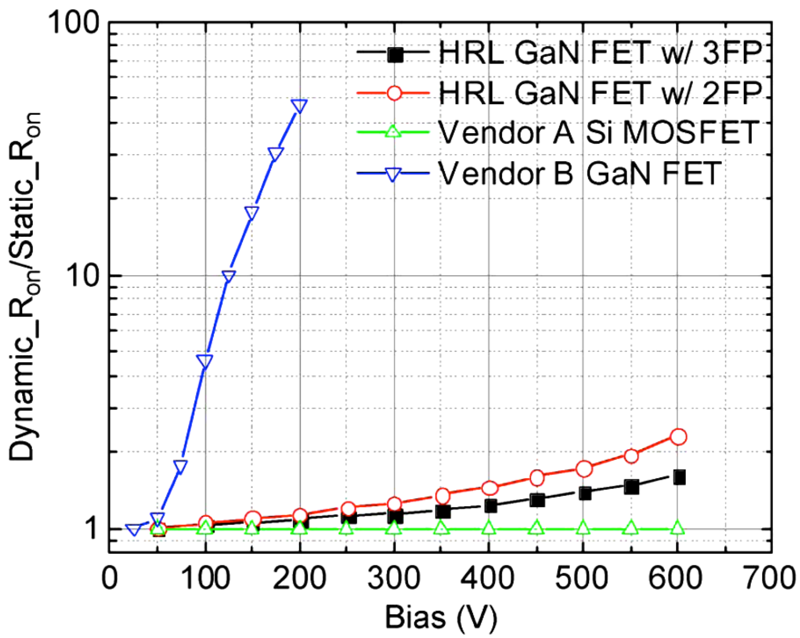


Mechanisms of passivation

- Surface states compensation --- charge balance
- Field-plate: passivation enhancement by E-field modification

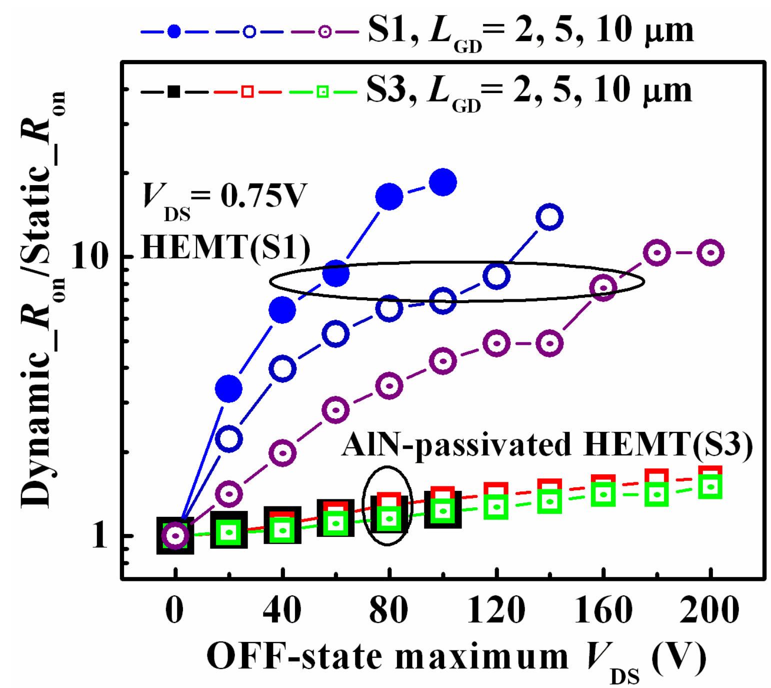
Current collapse reduction – low dynamic R_{ON}

SiNx passivation



- R. Chu, *et al., IEEE EDL,* vol.32, p.632, 2011

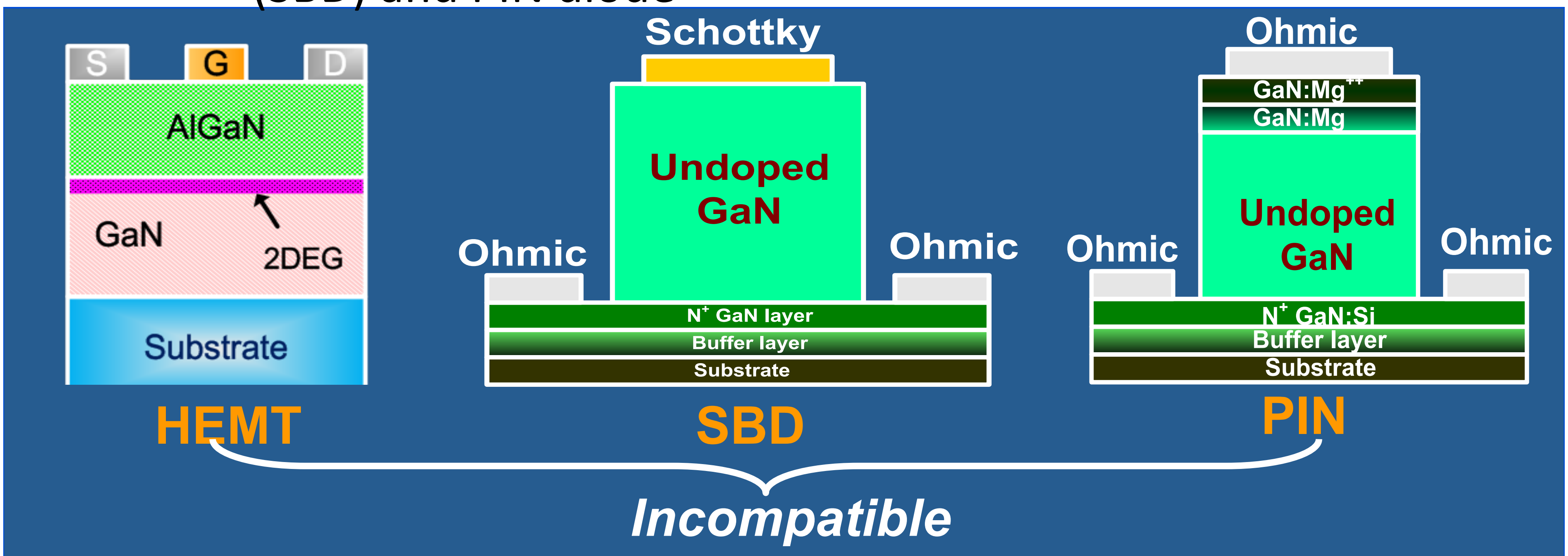
PEALD-AlN passivation



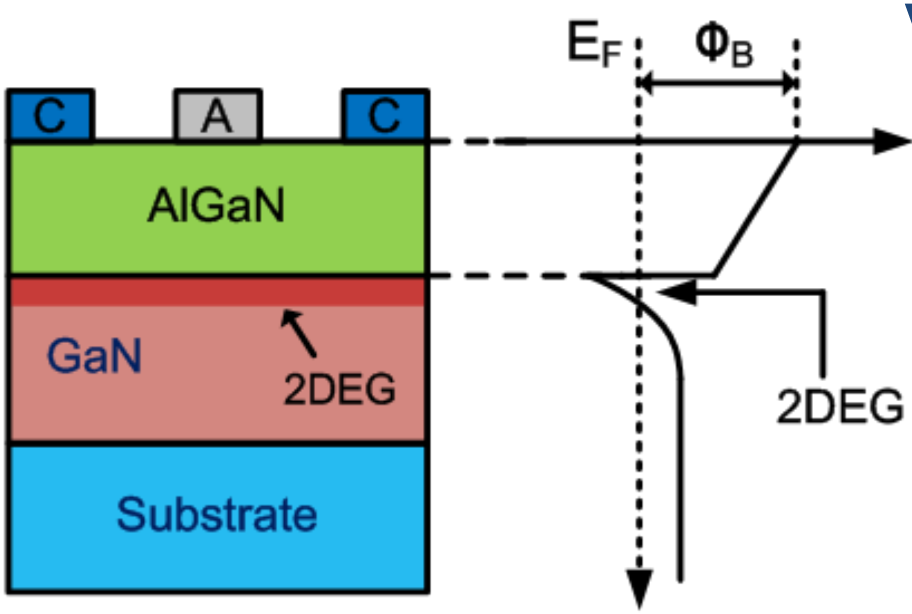
- **S. Huang, *et al.,* IEEE EDL, vol. 33, p. 516, 2012**

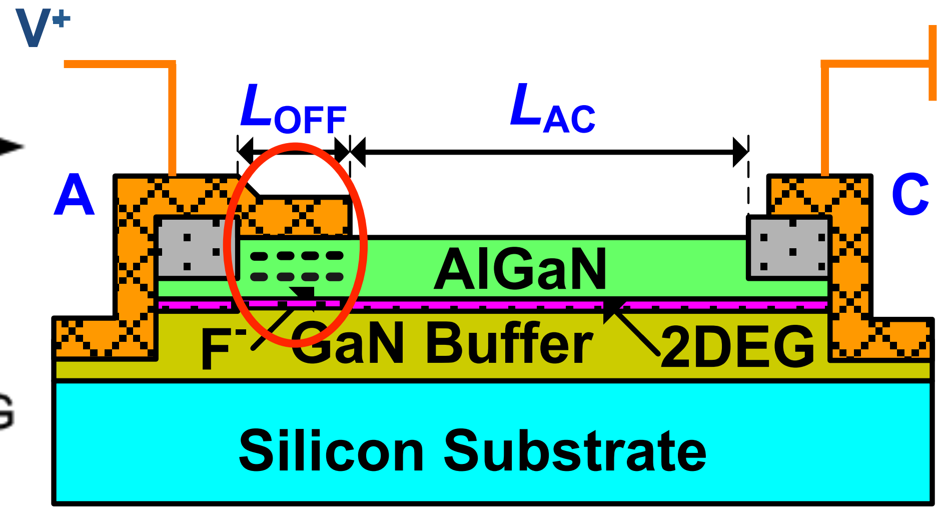
Challenge of GaN power device integration

- **_Transistor Switches_**
  - _Normally-off_ HEMT, MIS-HEMT
- **_Rectifiers_**
  - Conventional candidates: GaN Schottky barrier diode (SBD) and PIN diode



HEMT-compatible rectifiers

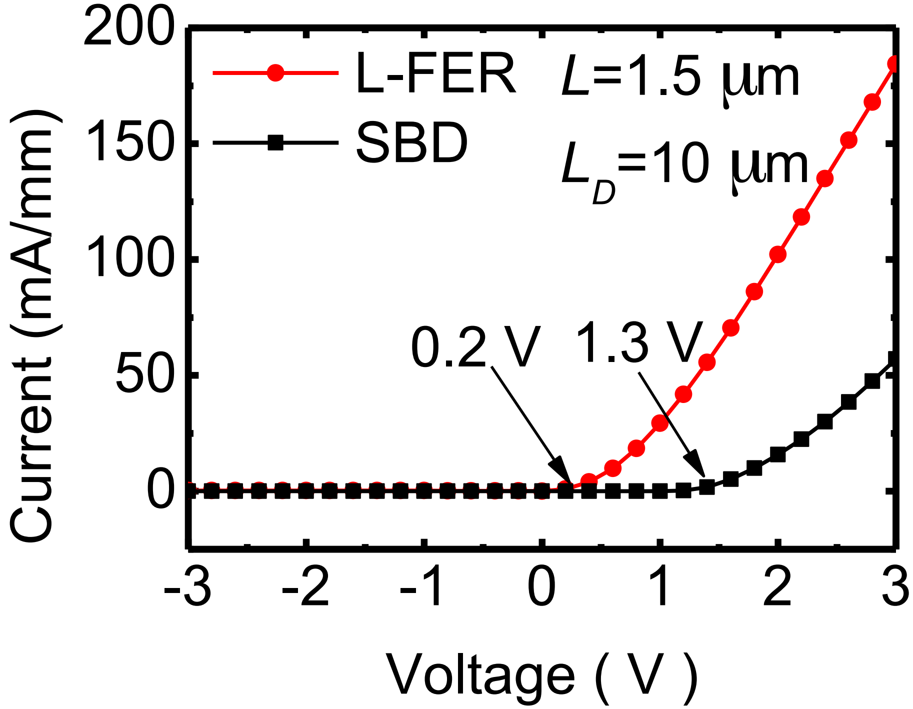


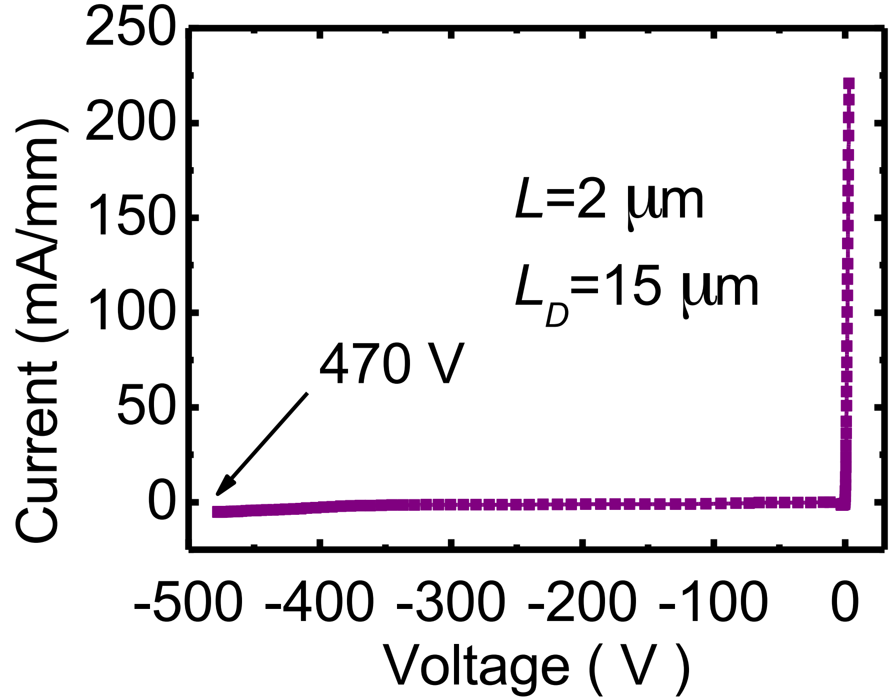


- ***Schottky barrier diode (SBD) on HEMT***
  - Higher turn-on voltage
  - ON-state reliability issue

- ***Lateral field-effect rectifier (L-FER)***
  - Low turn-on voltage and on-resistance
  - ***Sub-surface*** forward conduction – improved reliability

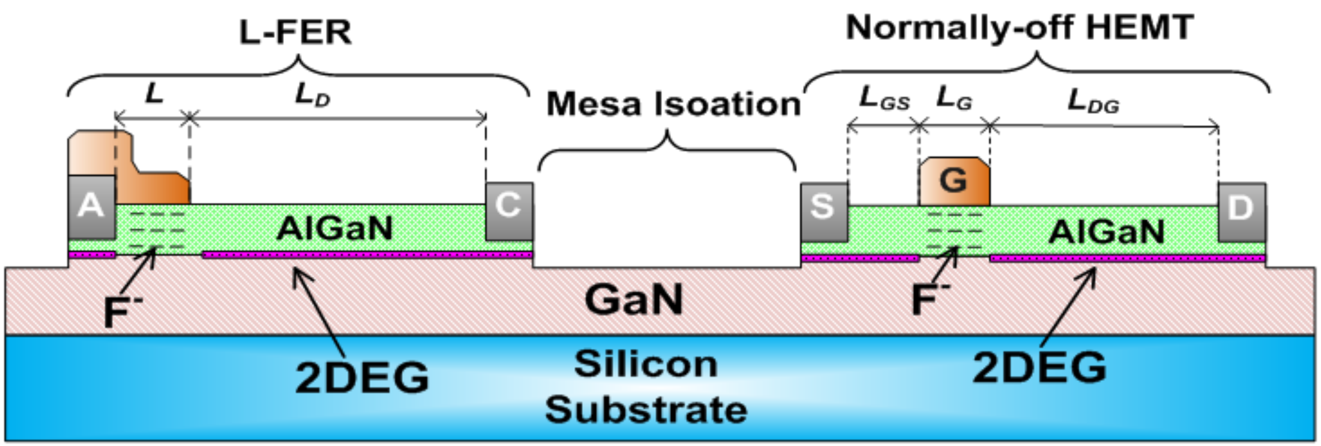
L-FER performance



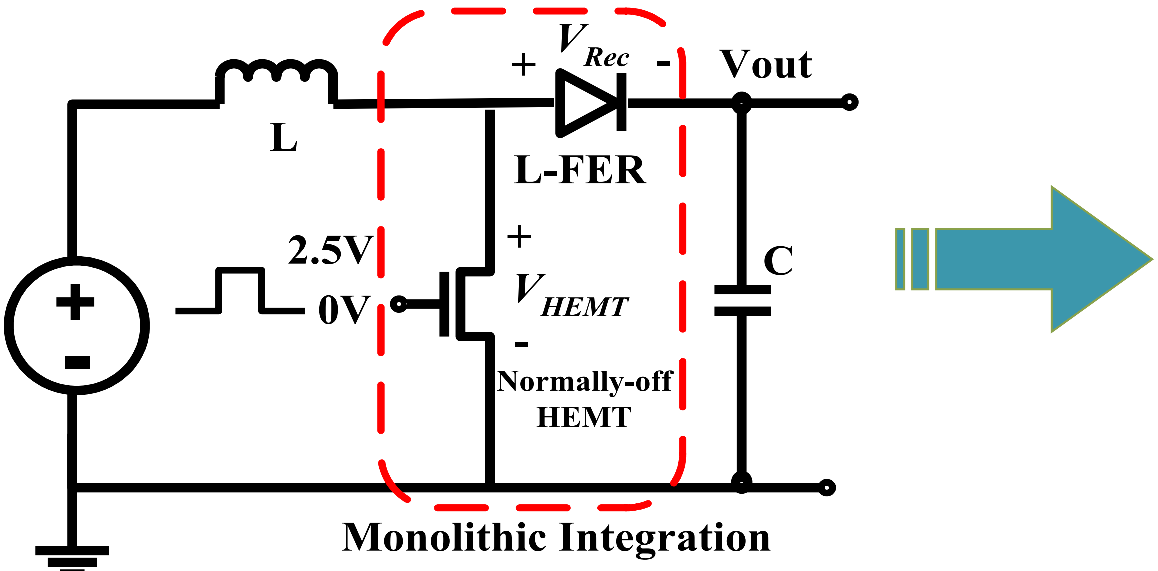


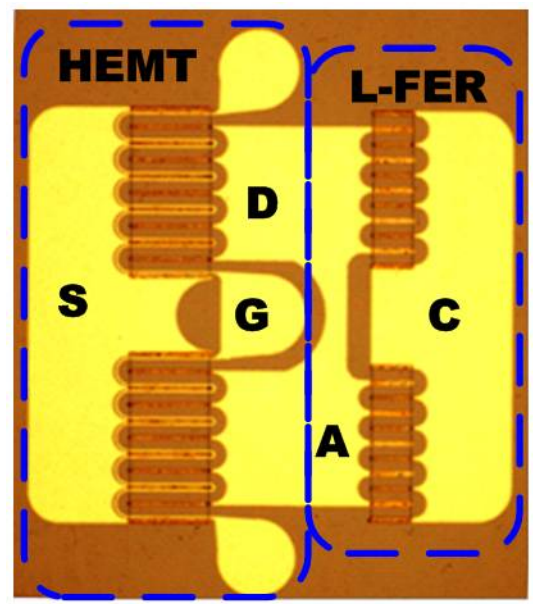
- $R_{ON,sp}$: **2.04 mΩ·cm²**
- ***BV*** **: 470 V**

Monolithic integration of HEMT and L-FER



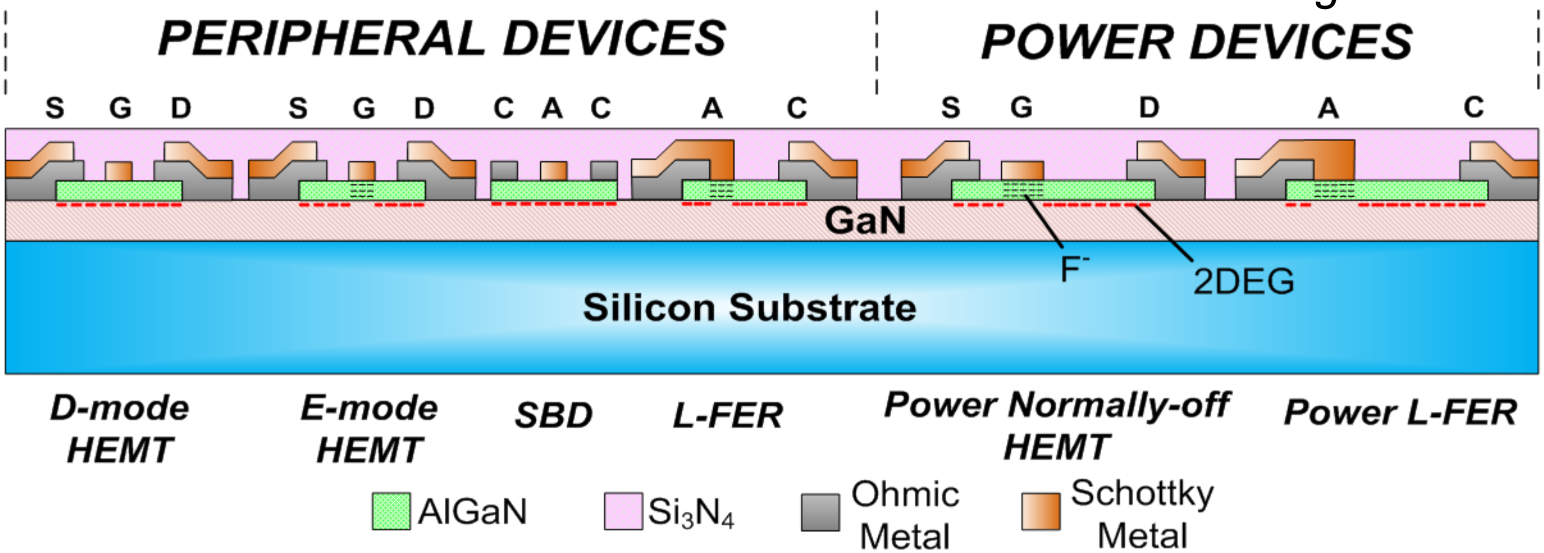
W. Chen, et al., *APL, 2008*, *IEEE EDL* 2009
W. Chen, et al., *IEDM 2008*.





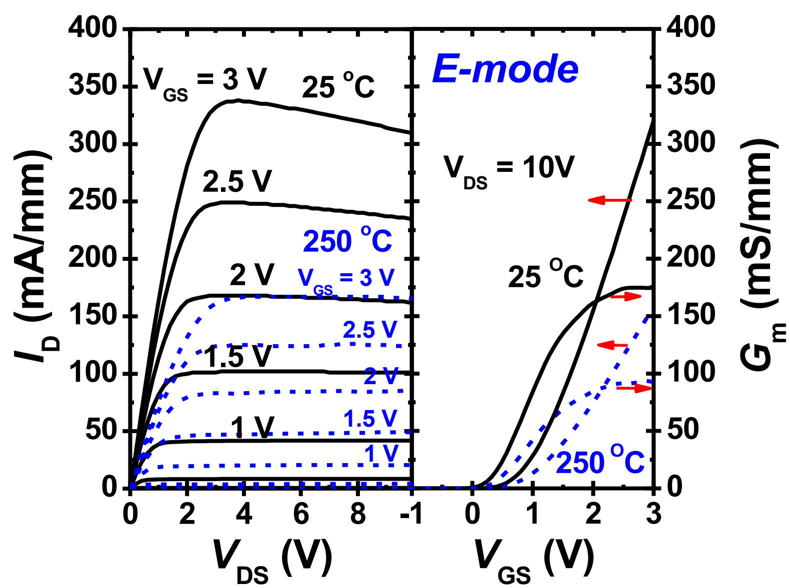
GaN Smart Power IC Platform

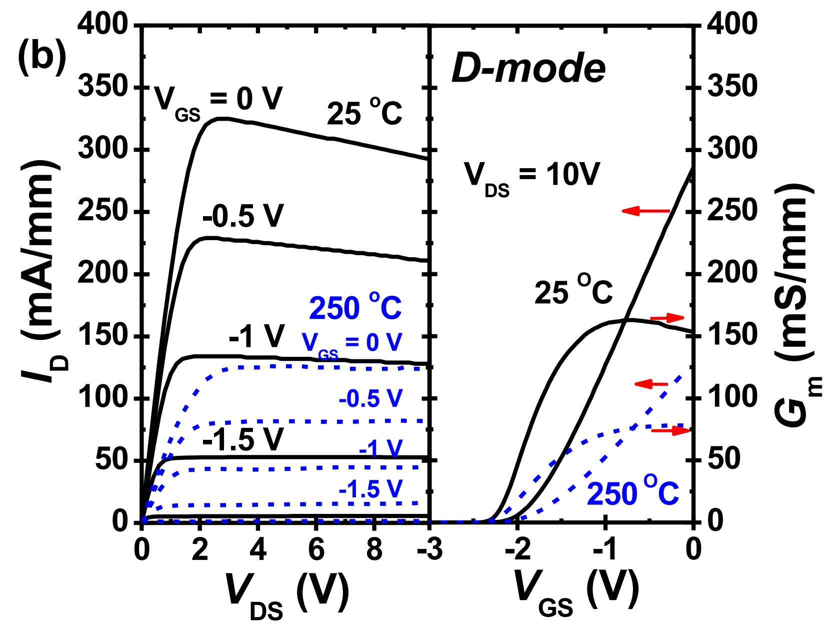
*K. Y. Wong et al. ISPSD'09

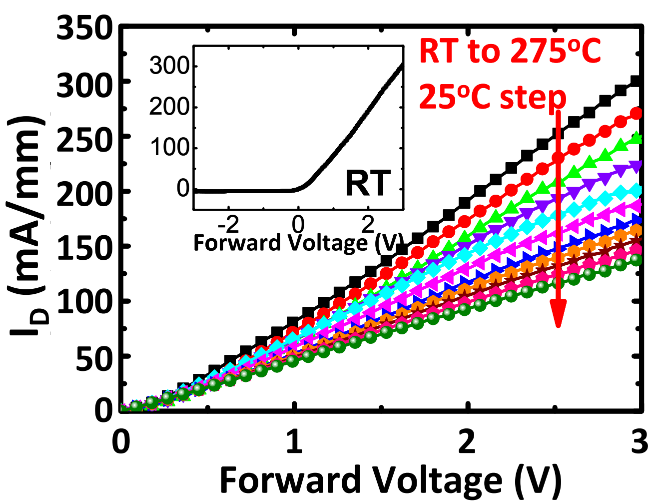


<table>
<tr><th>Core power devices</th><th colspan="2">Peripheral devices</th></tr>
<tr><td>❖ Normally-off HEMT
❖ Lateral Field-Effect Rectifier (L-FER)</td><td>Digital:
All-n-channel direct-coupled FET logic (DCFL)</td><td>Analog:
Sensing & Protection</td></tr>
</table>

Performance of integrated devices







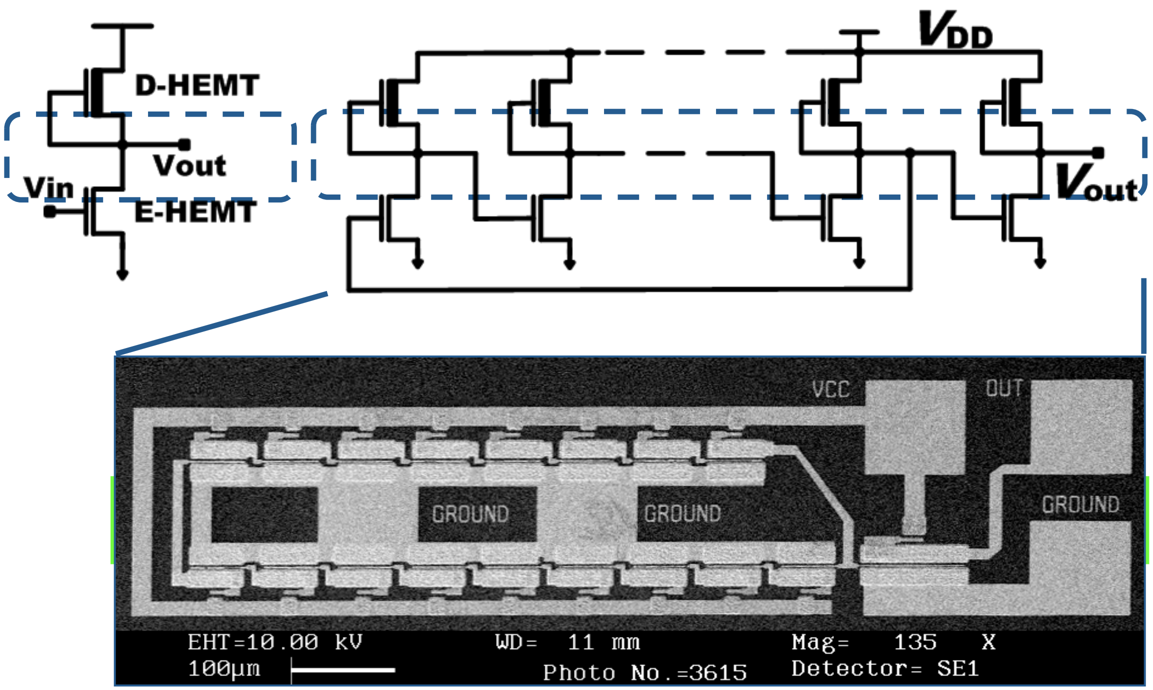
L-FER

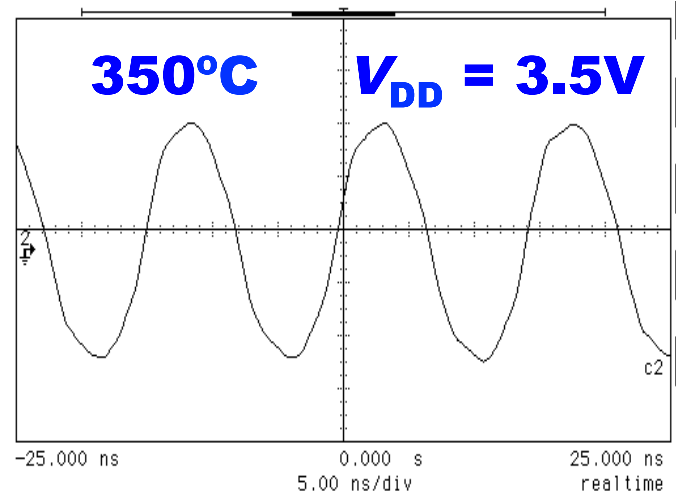
Well behaved devices within a wide range of operating temperature

Digital IC : Direct-Coupled FET Logic

DCFL Inverter

17 Stage DCFL Ring Oscillator



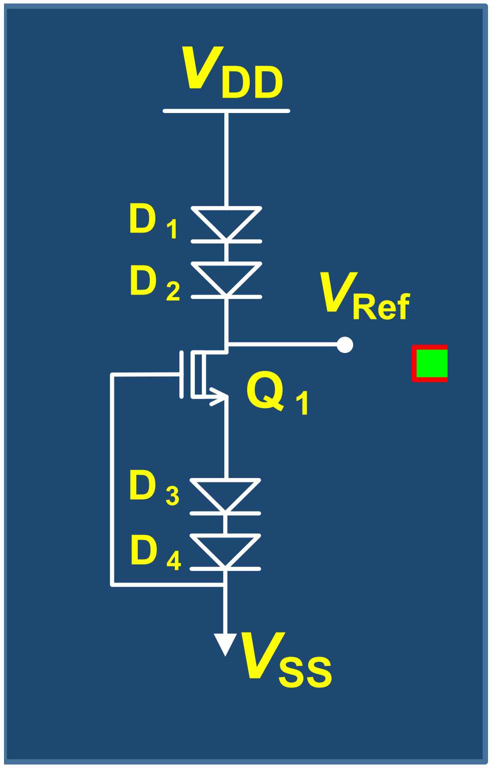


Output Signal

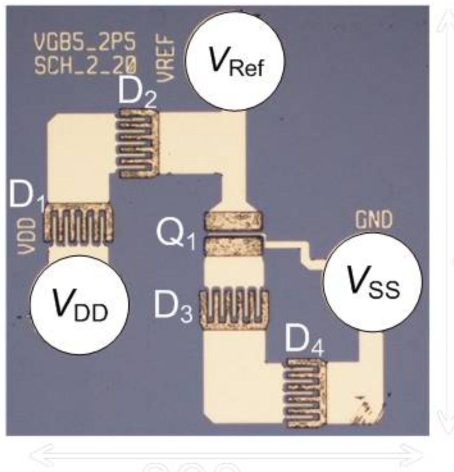
Proper operation: from room temp. to 350 °C (equipment limit)

* Y. Cai, *et al*. *IEDM Technical Digest*, (2005) and *EDL, (2007)*.

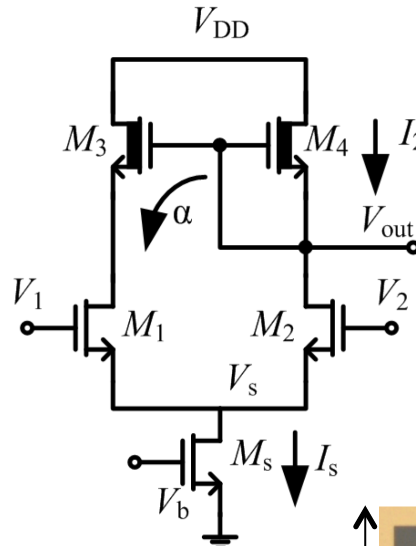
Some basic GaN mixed-signal functional blocks

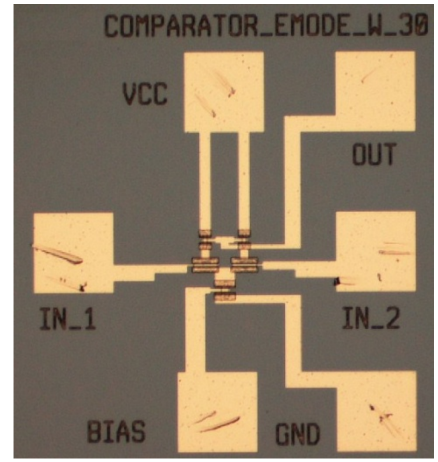


Voltage reference

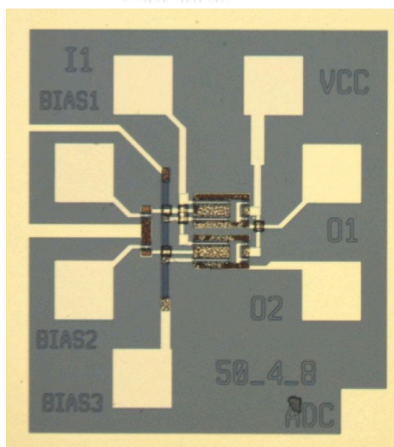


Bootstrap comparator

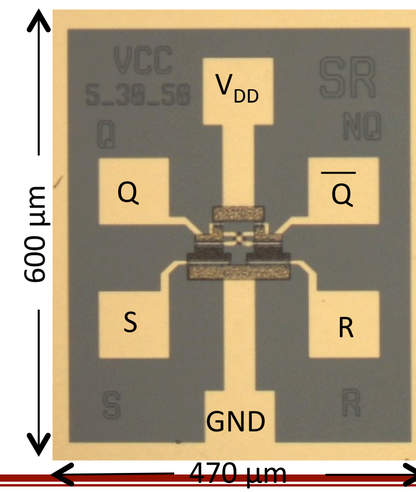




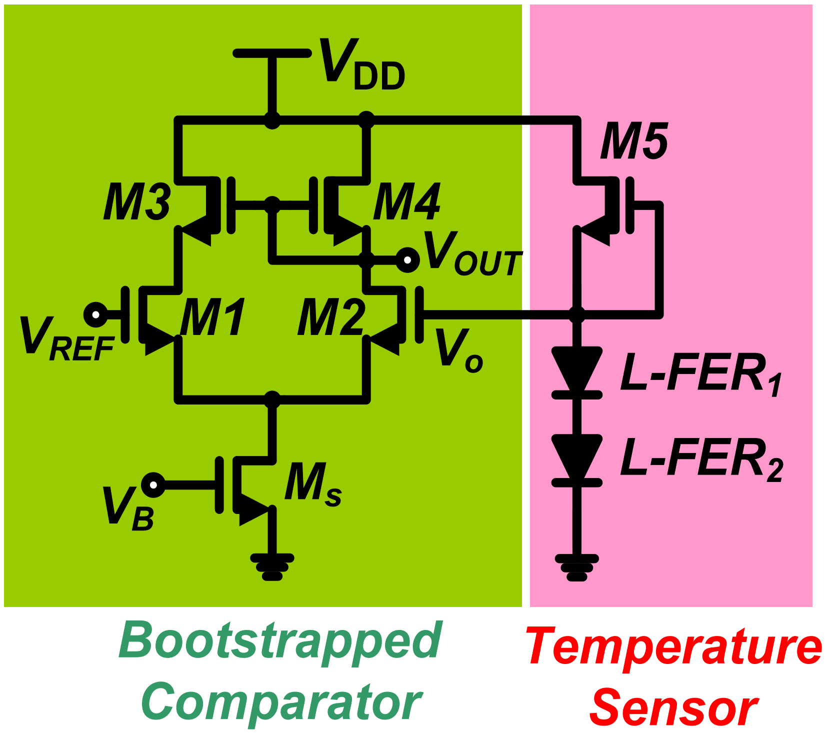
2-bit quantizer

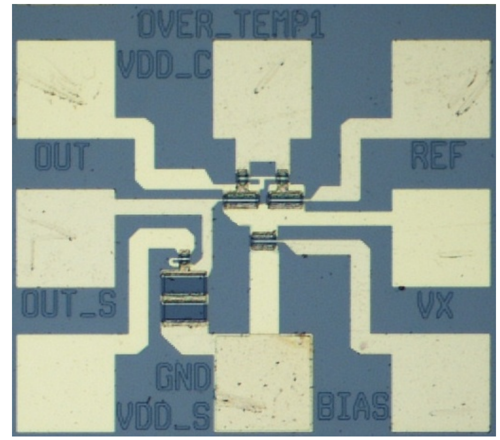


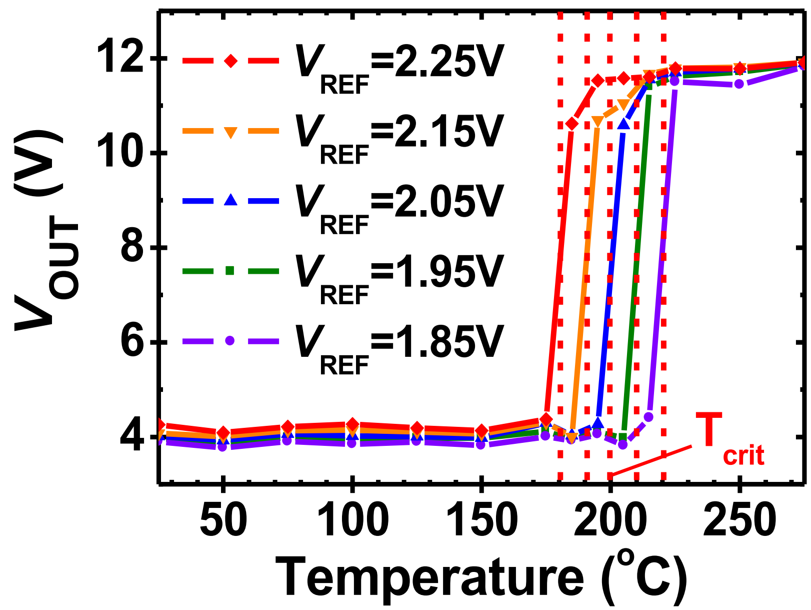
flip-flop



Over-temperature protection IC







* X. Liu *et al. EDL,* (2011).

Summary

- **GaN-on-Si power devices and ICs: an enabler for GaN-based PowerSOC**
  – high efficiency, small size and simple thermal management
- Integration of **normally-off HEMTs** and **HEMT-compatible field-effect rectifiers** enables single-chip solution to switch-mode power converters.
- **GaN smart power ICs** with mixed-signal protection/ control functions will enable more robust power converter solution.