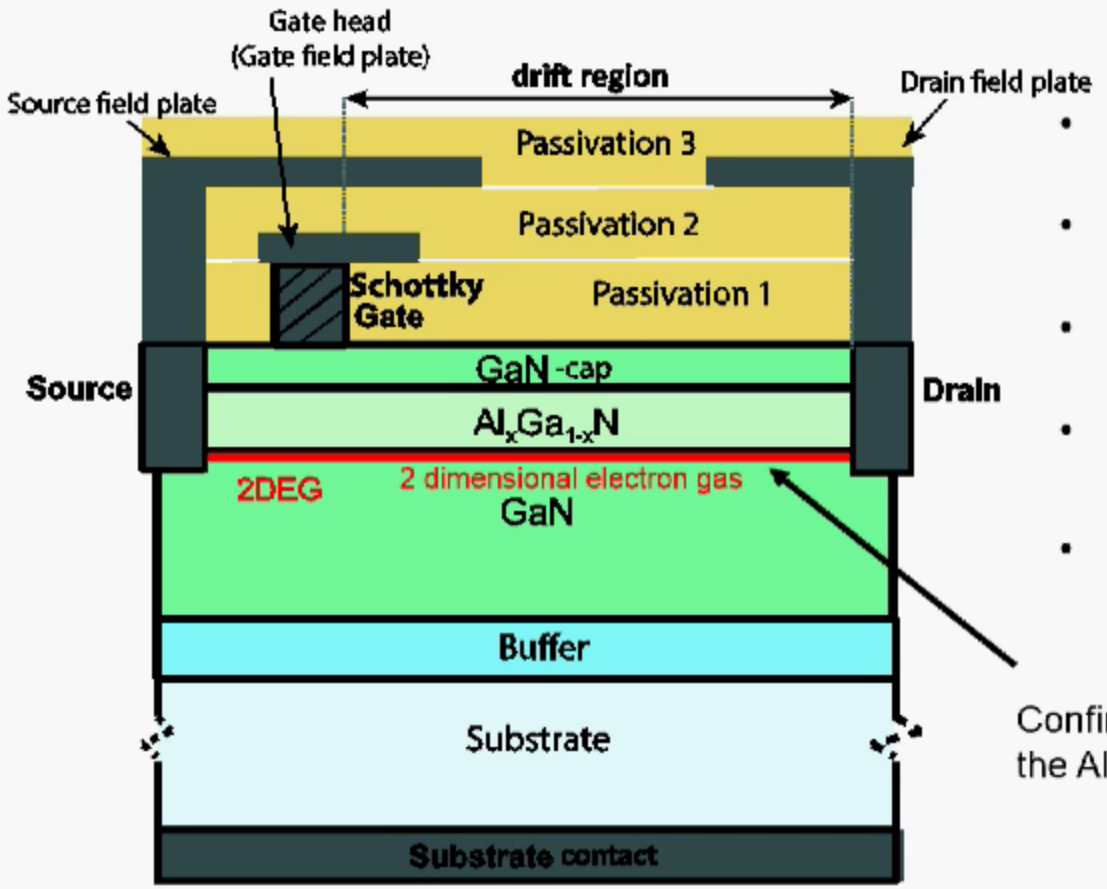
GaN based devices

HEMT
High Electron Mobility Transistor

- First appear in 2004 in Japan by Eudyna Corporation for RF applications.



- 4 terminals device
- Normally-on (Depletion mode)
- Heterostructure-based
- High electron density in the channel (2DEG)
- Gate-to-Drain distance withstand the electric field in the off-state

Confinement of electrons at the AlGaN/GaN interface

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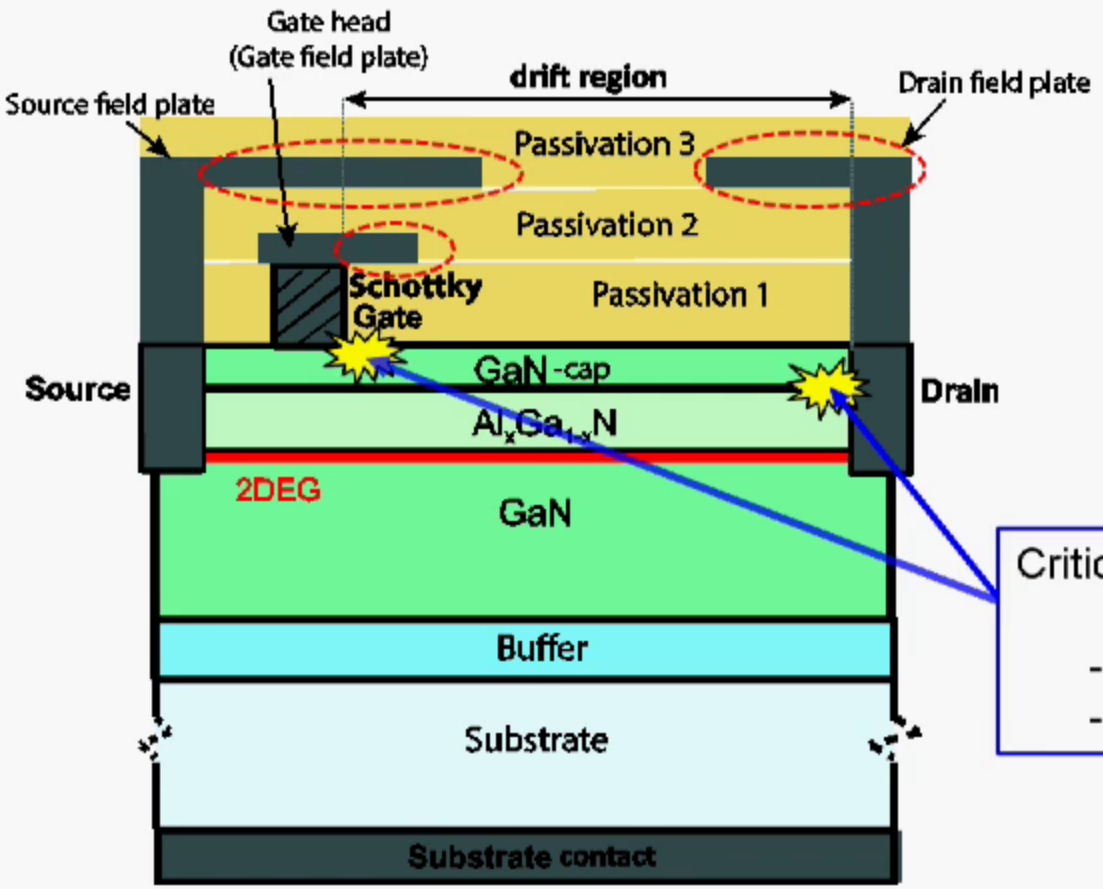
Field plates



- Two **purposes**:

1. Increase the breakdown by reducing the peak of the electric field.

2. Alleviate effects of high-electric-field- related trapping phenomena

Critical points for high electric field:

- Drain-side of the gate contact
- Drain contact

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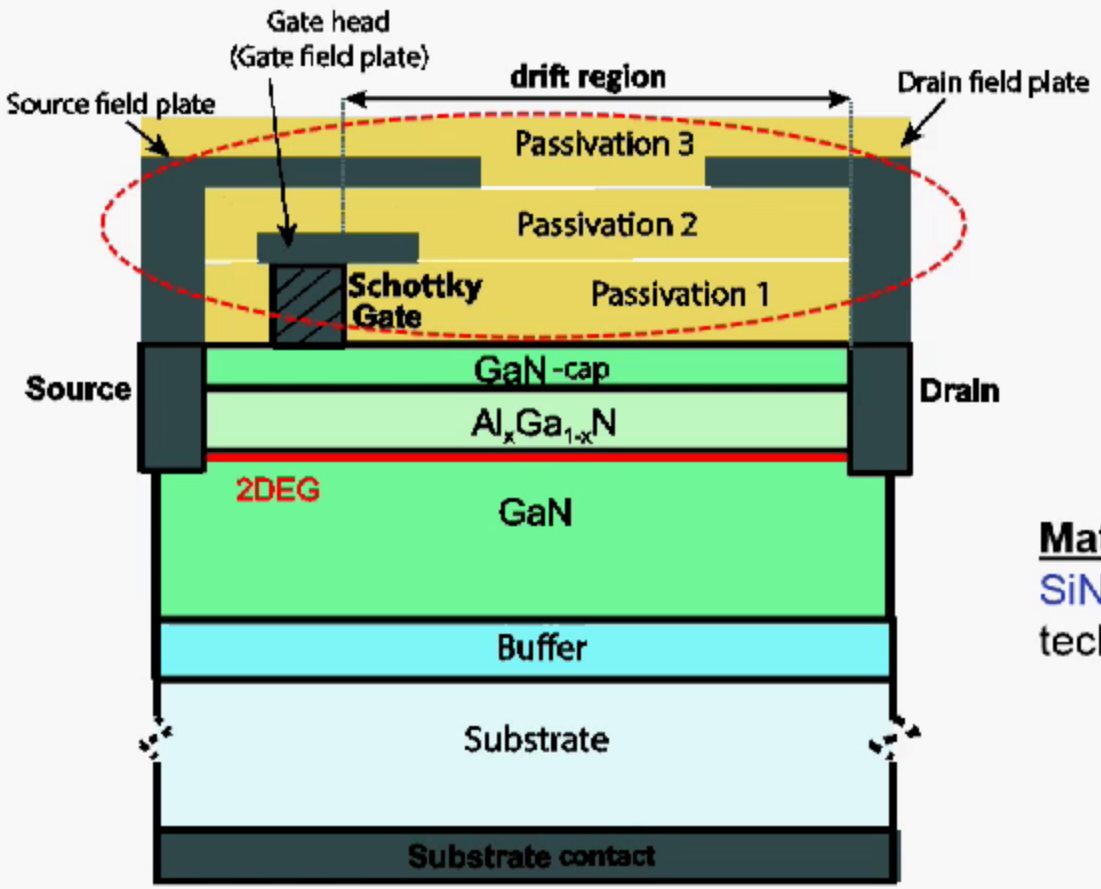
Passivation layers



- Three **purposes**:

1. Alleviate the surface-trap related degradation mechanisms.
2. Field plate design.
3. Final passivation of the devices

Materials used for passivation:
SiN (most common) with different deposition techinques (LPCVD, PECVD, RS)

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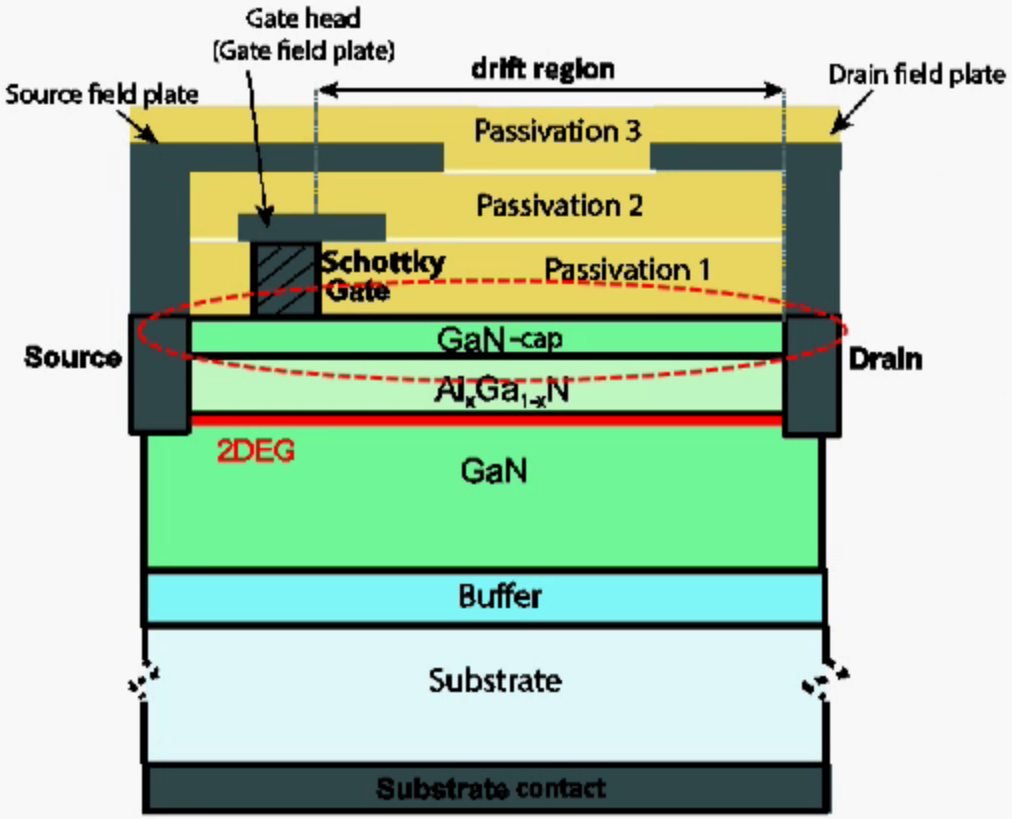
GaN-cap layer



Purposes:

1. Reduce the reverse leakage current through the Schottky contact.
2. Increase in the electric field strength in the AlGaN layer in the off-state (with consequent improved reliability).
3. Increase in power efficiency by increasing the thickness.

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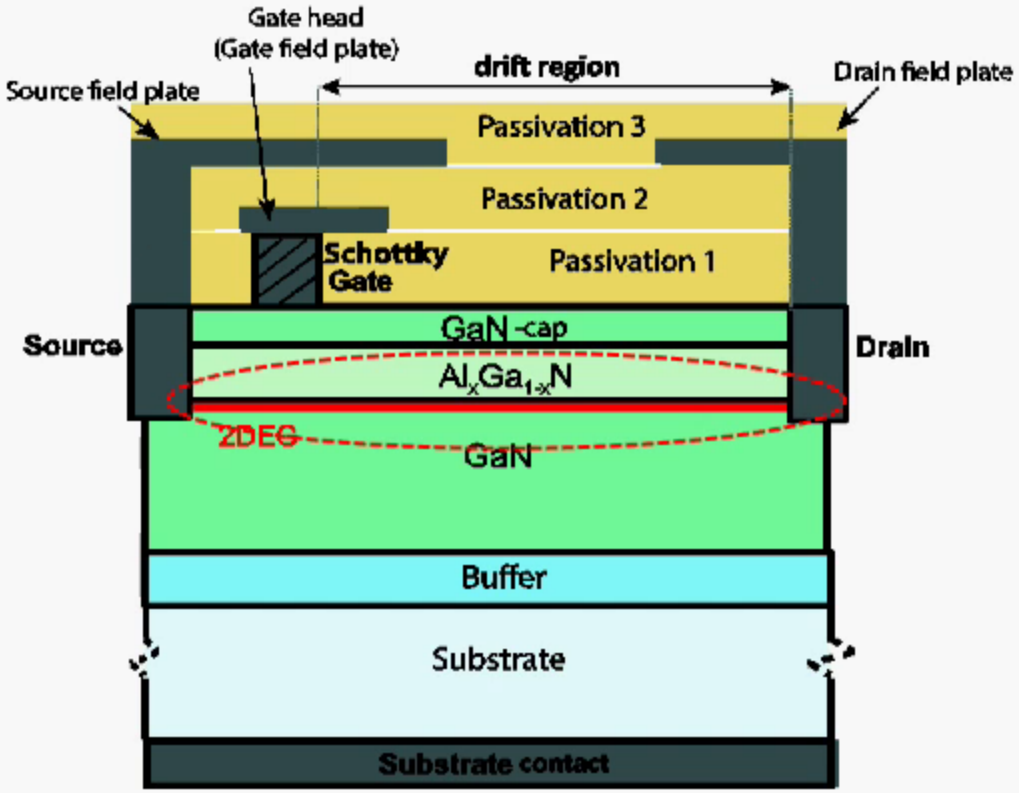
AlGaN/GaN heterostructure



- It is the core of the HEMT
- Thickness and doping of the GaN layer affect the off-state performance

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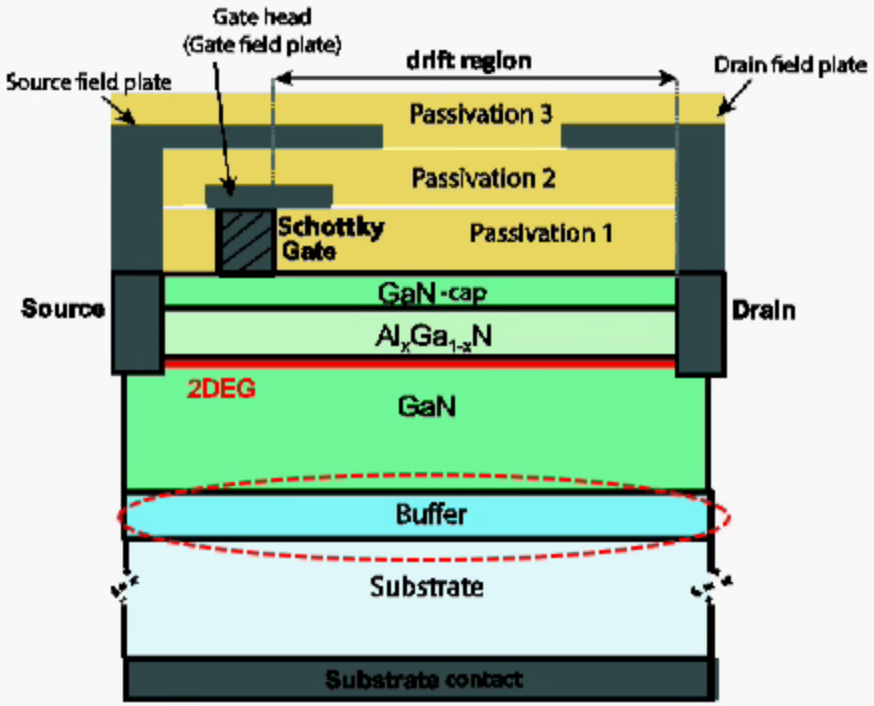
Buffer



Purpose:

It affects the structural and optical properties of the GaN layer grown above, thus the on- and off-state electrical characteristics of the device.

Most common buffer layers for Si substrates:

- Single layer of AlN or AlGaN
- Superlattice structure made of GaN and Al(Ga)N layers

Increasing the buffer thickness yields a reduced substrate leakage

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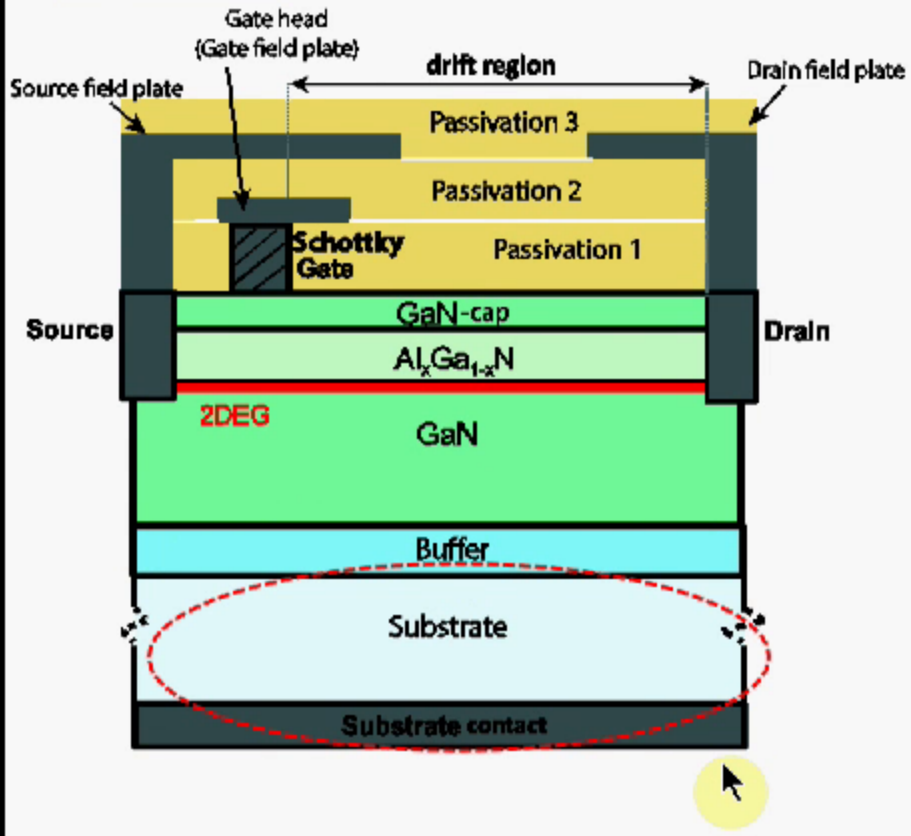
Substrate



Three possible substrates for GaN-Devices:

- **Sapphire** (Al_2O_3)
  - ✓ Semi-insulating, can withstand high growth temperatures, relatively cheap
  - × Very low thermal conductivity, large lattice mismatch, large CTE mismatch
- **Silicon carbide** (SiC)
  - ✓ High thermal conductivity, low lattice mismatch, relatively low CTE mismatch
  - × Cost, crystallographic defects
- **Silicon** (Si)
  - ✓ Low cost, excellent availability of large diameters, acceptable thermal conductivity, processing in standard silicon fabs
  - × Large lattice mismatch, very large CTE mismatch

HEMT
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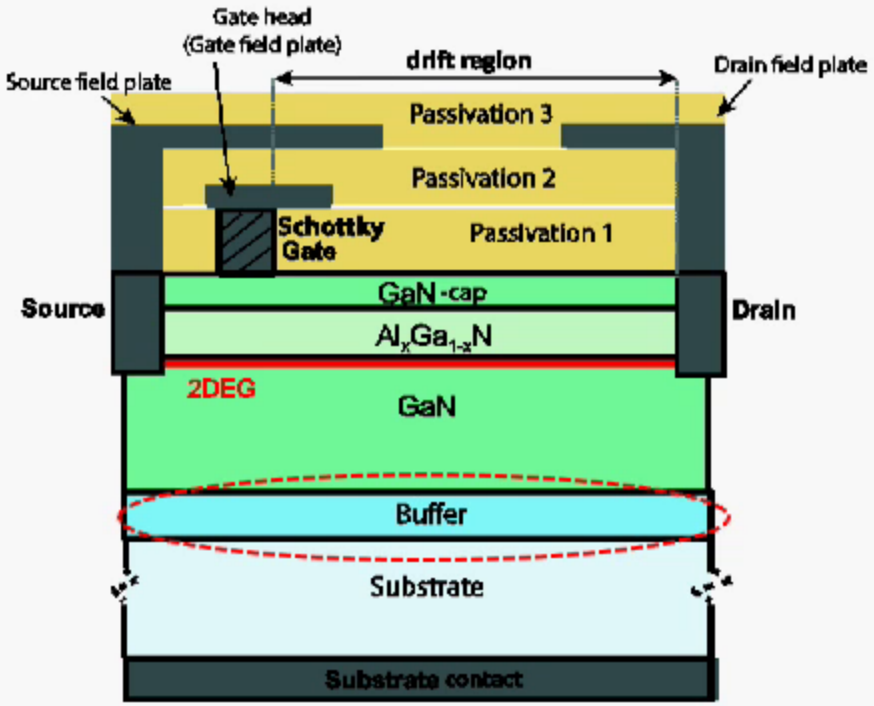

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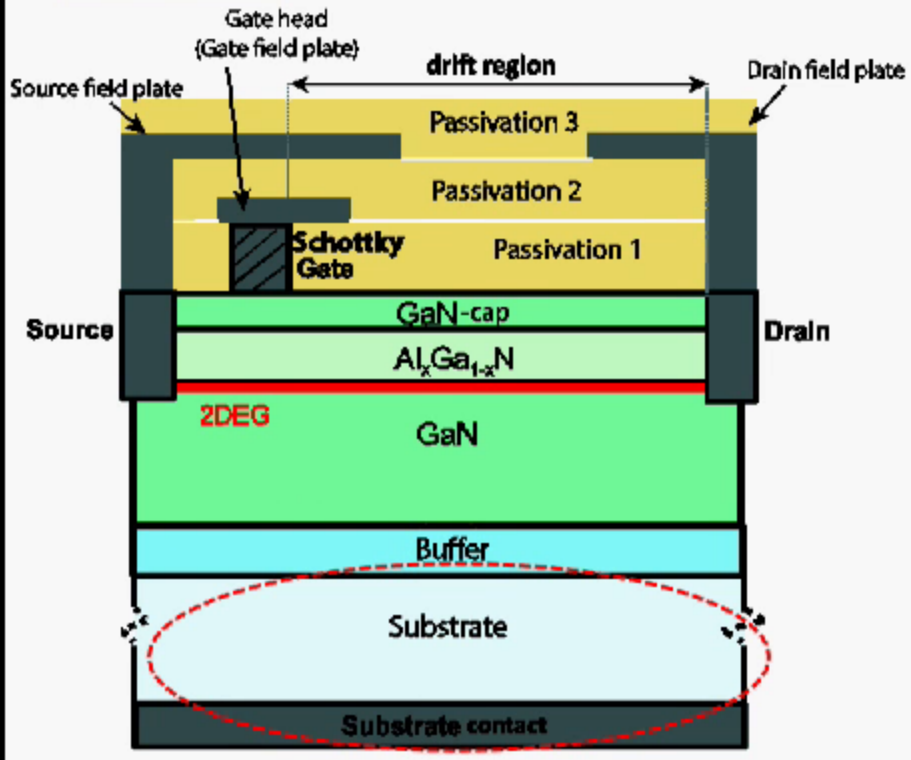

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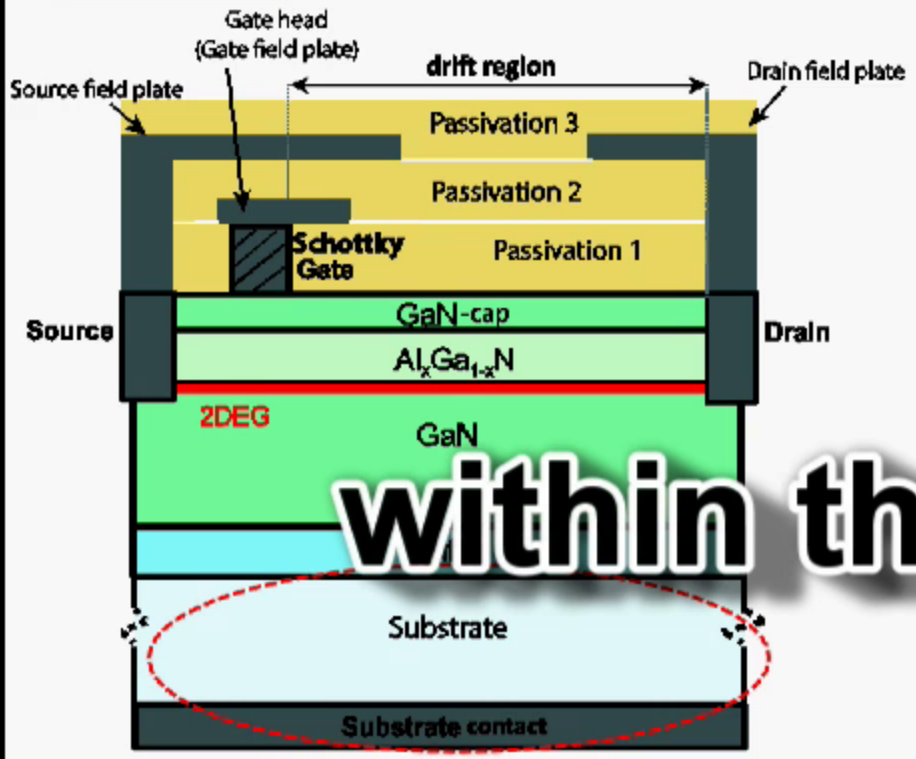

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  - [illegible]
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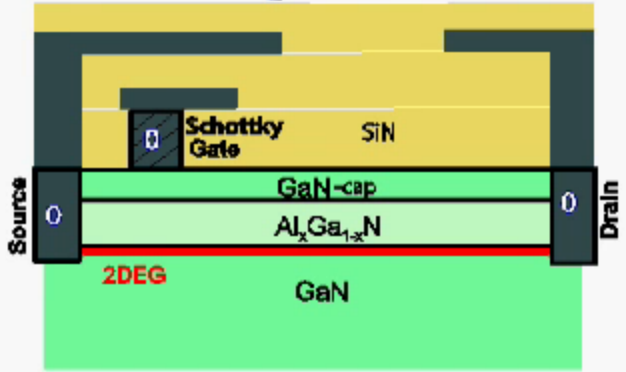
within the GaN layer

HEMT Operation mode

Four **bias conditions**:

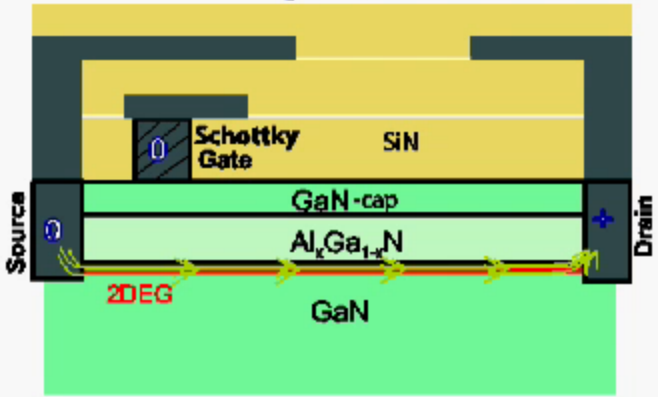
Zero Bias

- $V_g = 0$ V
- $V_s = 0$ V
- $V_d = 0$ V



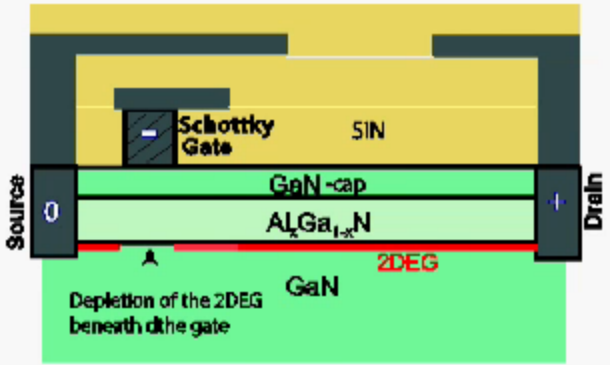
On-state

- $V_{th} < V_{gs} < V_{Schottky}$
- $V_{ds} > 0$ V



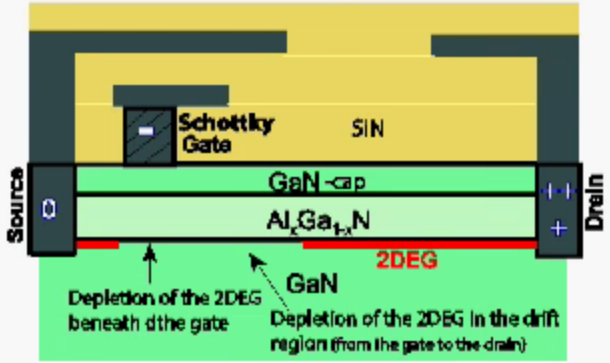
Off-state

- $V_{gs} < V_{th}$



Blocking mode

- $V_{gs} < V_{th}$
- $V_{ds} >> 0$ V



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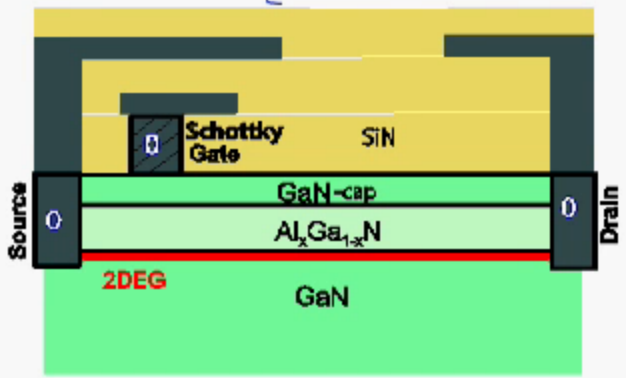
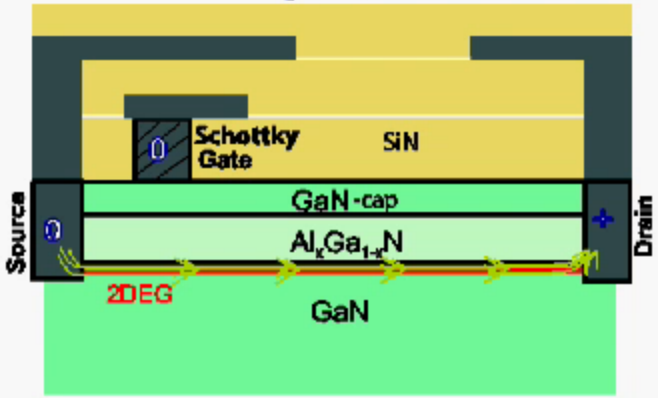


On-state

- $V_{th} < V_{gs} < V_{Schottky}$
- $V_{ds} > 0$ V



Off-state

- $V_{gs} < V_{th}$

Blocking mode

- $V_{gs} < V_{th}$
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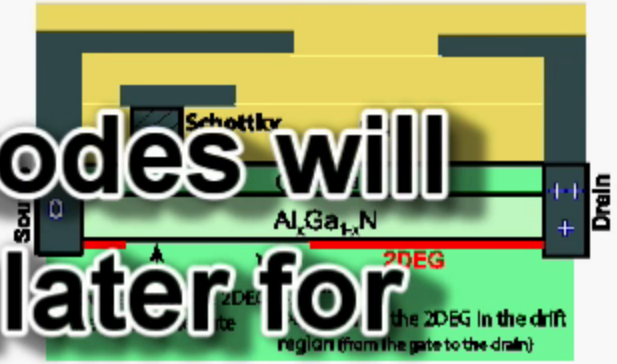

Operation modes will be reharsed later for better understanding

Now a reharse of the Operation modes of the normally ON HEMT device

HEMT Operation mode

Four **bias conditions**:

Zero Bias

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- $V_s = 0$ V
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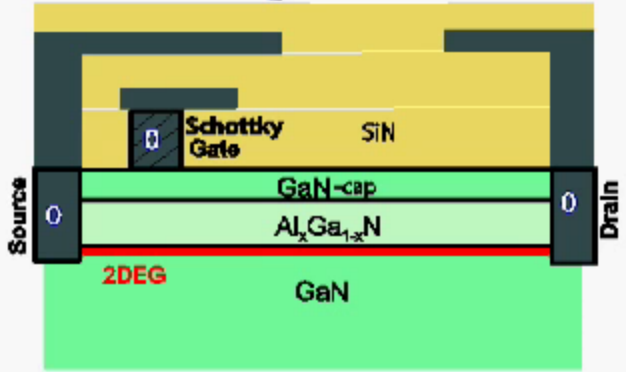
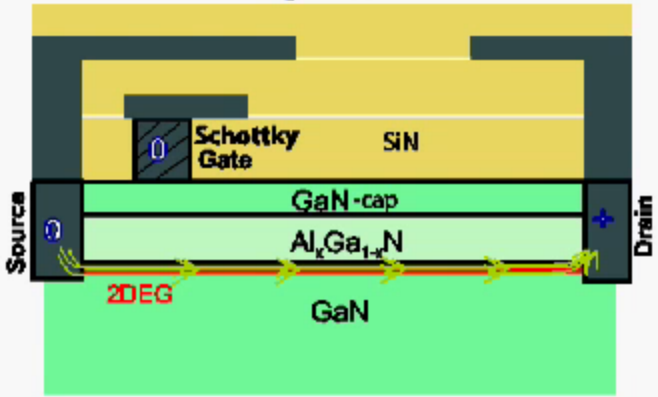


On-state

- $V_{th} < V_{gs} < V_{Schottky}$
- $V_{ds} > 0$ V



Off-state

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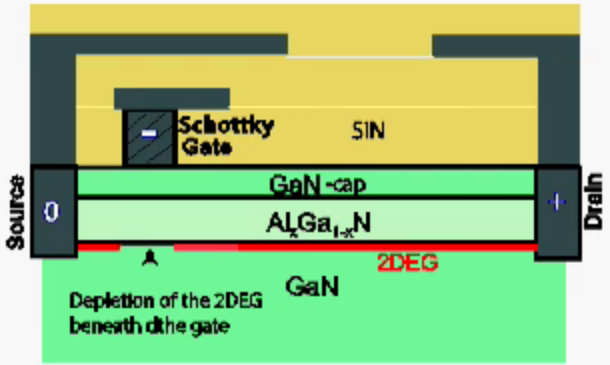

Blocking mode

- $V_{gs} < V_{th}$
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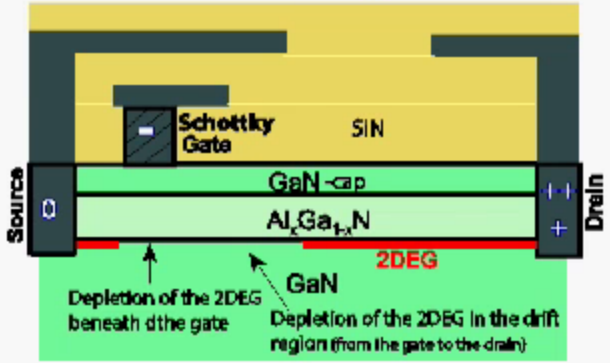
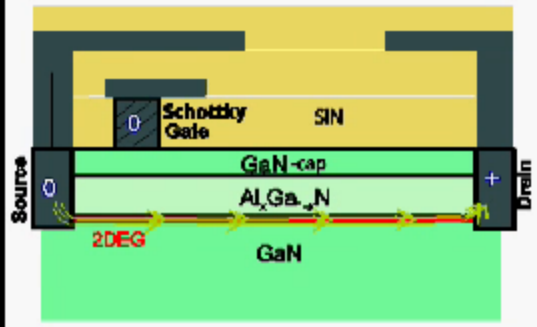


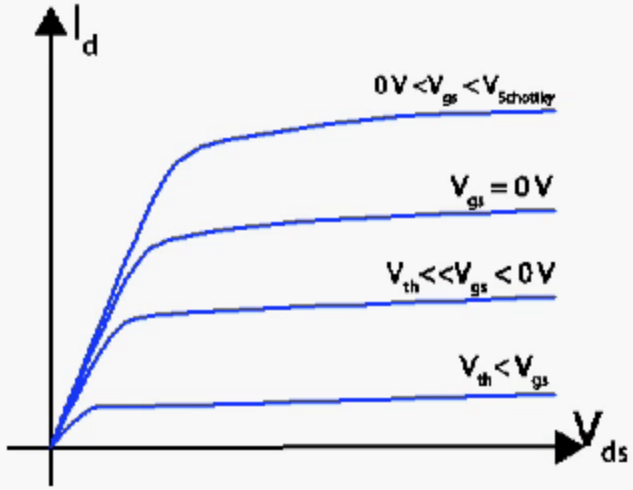
HEMT Operation mode: On-state

ON-State bias

- $V_{th} < V_{gs} < V_{Schottky}$
- $V_{ds} > 0$ V

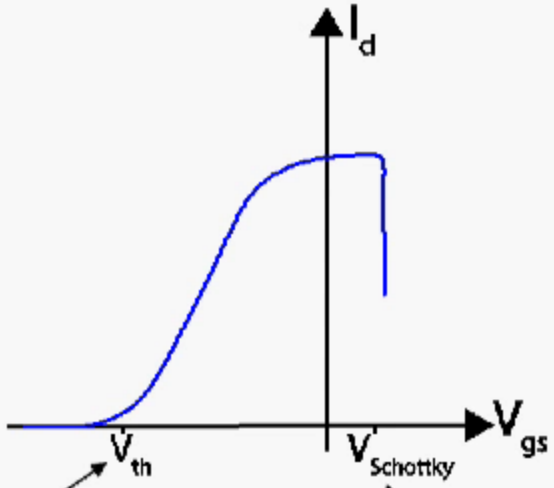


Output characteristics



Transfer characteristics

$V_{ds} > 0$ V



Typical threshold voltage V_{th} -2 V to -4 V

Typical Schottky turn-on voltage +1V to +2

- The electron current flows horizontally through the 2DEG channel as a positive V_{ds} is applied
- When V_{gs} reaches the $V_{schottky}$ the Schottky diode turn on and the electron current flows between the source and the gate. → The drain current decrease abruptly.

Origin of the 2DEG

- Surface donor-like states are considered to be the major source of electrons in the structure.

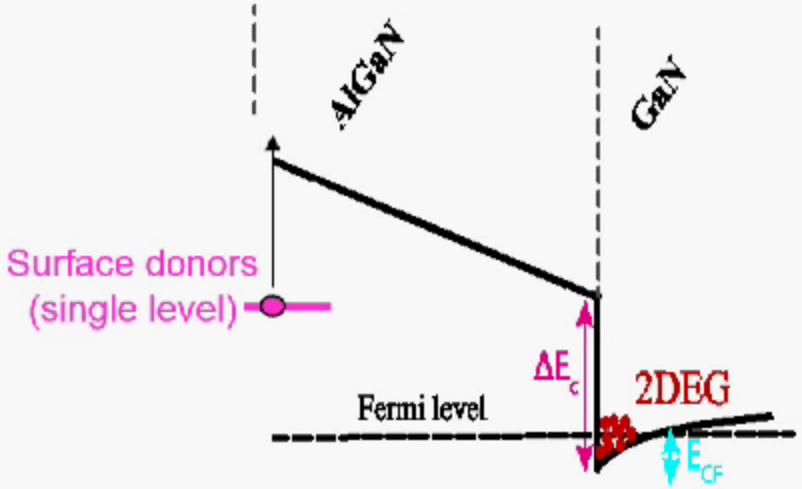
[Longobardi, Giorgia, et al. EDL, (2014): 1-1.]
[J. P. Ibbetson *et al.*, Appl. Phys. Lett. **77 (2)**, 250 (2000)]

- They have an essential role in the charge neutrality in the structure.

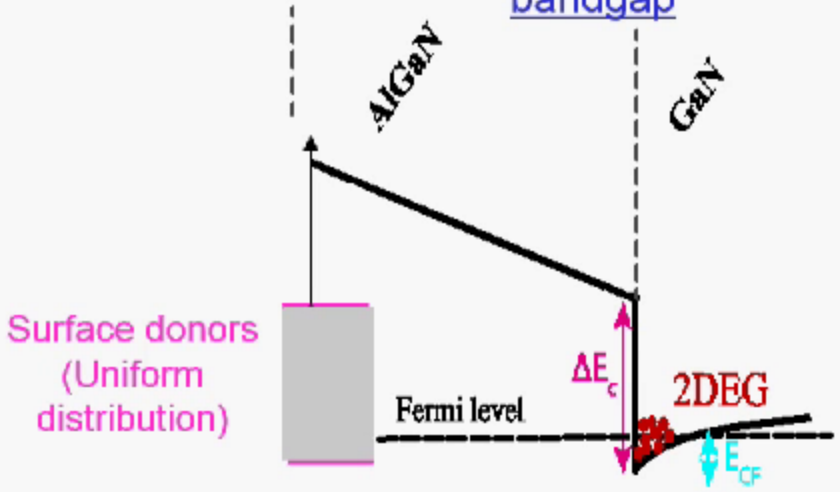
⇩

- They are crucial trap states that change the electrical behaviour of the AlGaN/GaN interface and have an impact on the stability and reliability of GaN based devices

Single energy level



Uniform distribution within the bandgap



HEMT Operation mode: On-state

ON-State bias

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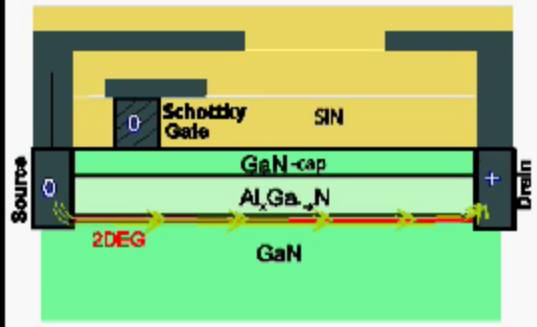
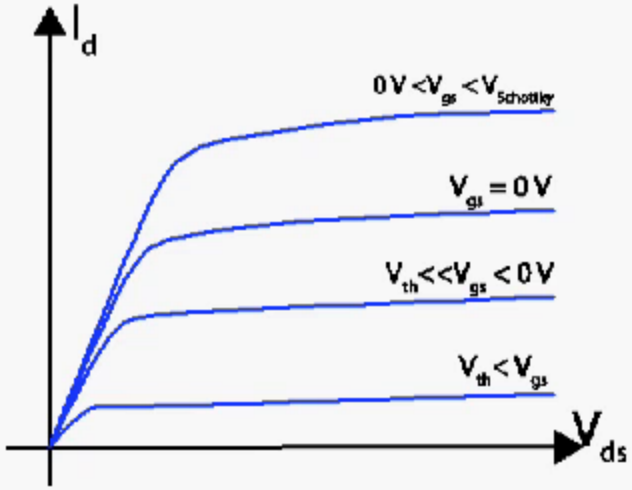
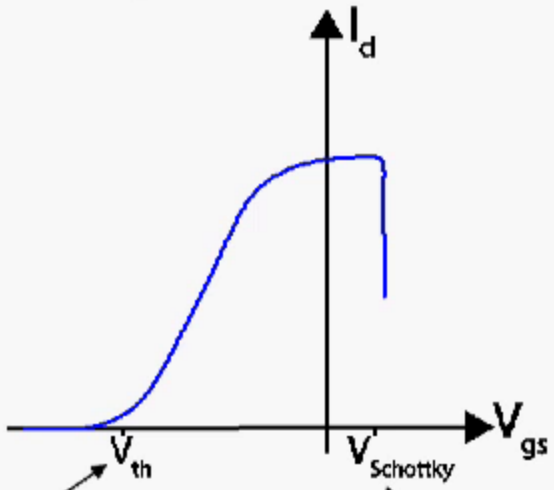


Output characteristics



Transfer characteristics

$V_{ds} > 0$ V



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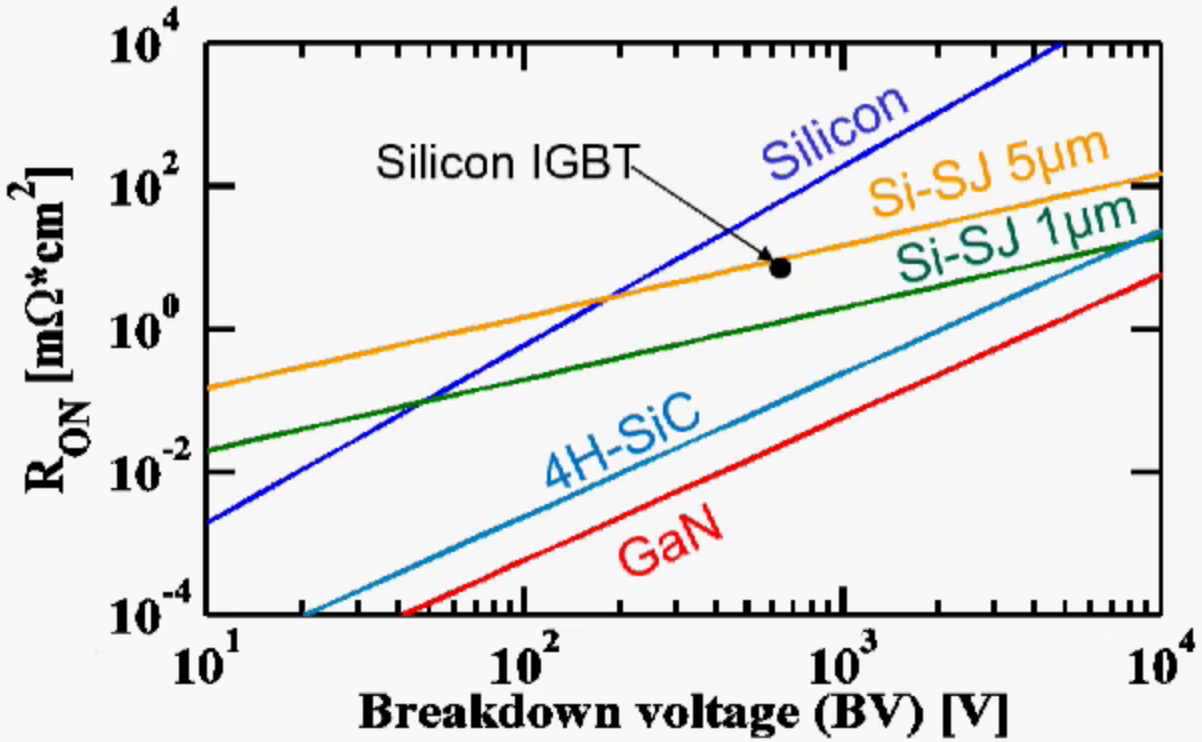
BV vs Ron trade-off
The complete scenario

- **Wide bandgap materials** such as Silicon Carbide (SiC) and Gallium Nitride (GaN) overtake the limit of Si and Si-SJ technologies due to their material properties.



GaN devices are based on lateral technologies for which the trade-off is:

$$R_{ON} = \frac{BV^2}{q\mu_n n_s E_c^{\,2}}$$

Electron mobility

Sheet electron density in the channel [cm^{-2}]

Critical Electri Field