2nd

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Wide Bandgap and Ultra Wide Bandgap Power Devices

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA
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Outline

- Introduction to WBG power devices
  - Key Performance Indicators (KPIs)
  - Material and device properties
  - Market and application areas: GaN vs SiC
- GaN transistors: commercial and emerging normally-OFF architectures
- Reliability: static vs dynamic testing
- The WBG Pilot Line Initiative
- Conclusions

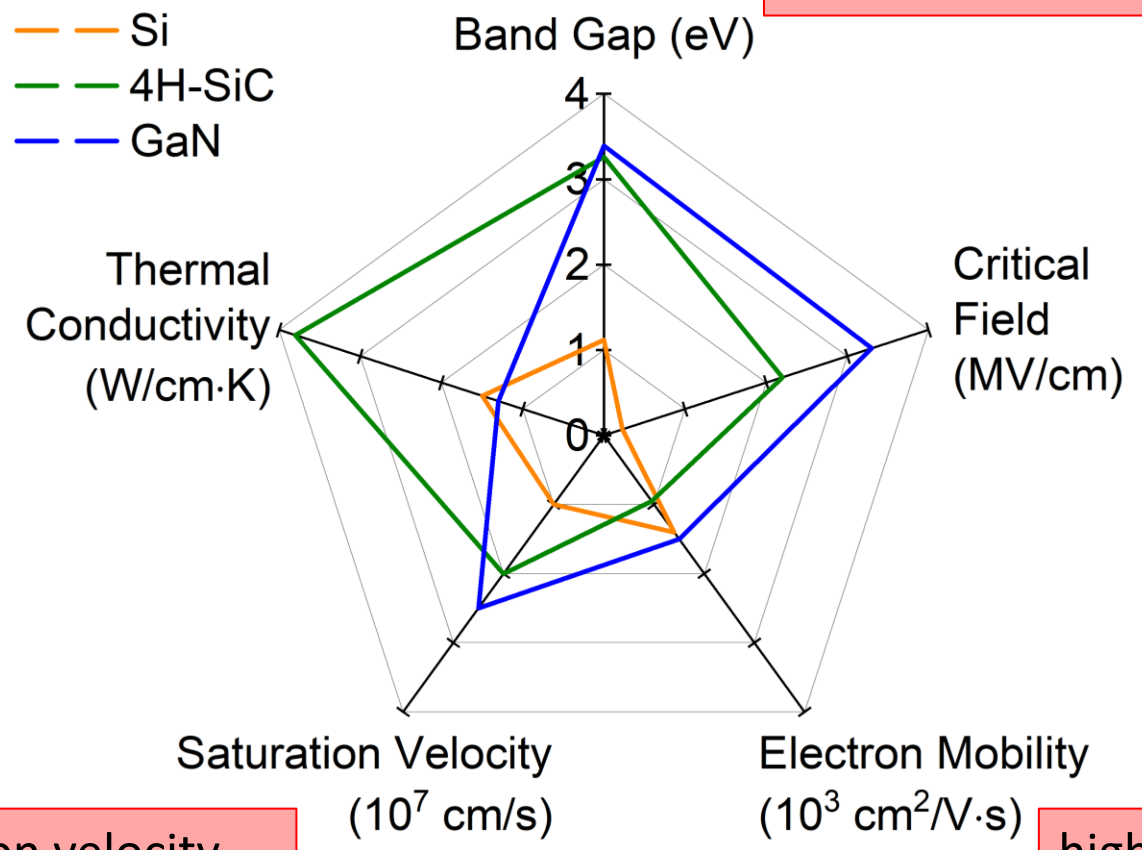
KPIs of power semiconductor devices

1. **High breakdown voltage:** to sustain high operating voltages
2. **Low ON-resistance:** to reduce conduction losses and improve efficiency
3. **Fast switching:** to minimize switching losses
4. **Efficient heat dissipation:** to limit performance degradation and improve reliability
5. **Cost-effectiveness:** to enable large-scale adoption

Material/Device Properties: Si, SiC, GaN

Wider bandgap reduces intrinsic carrier concentration and leakage current

Higher thermal conductivity improves heat removal and enables high power density



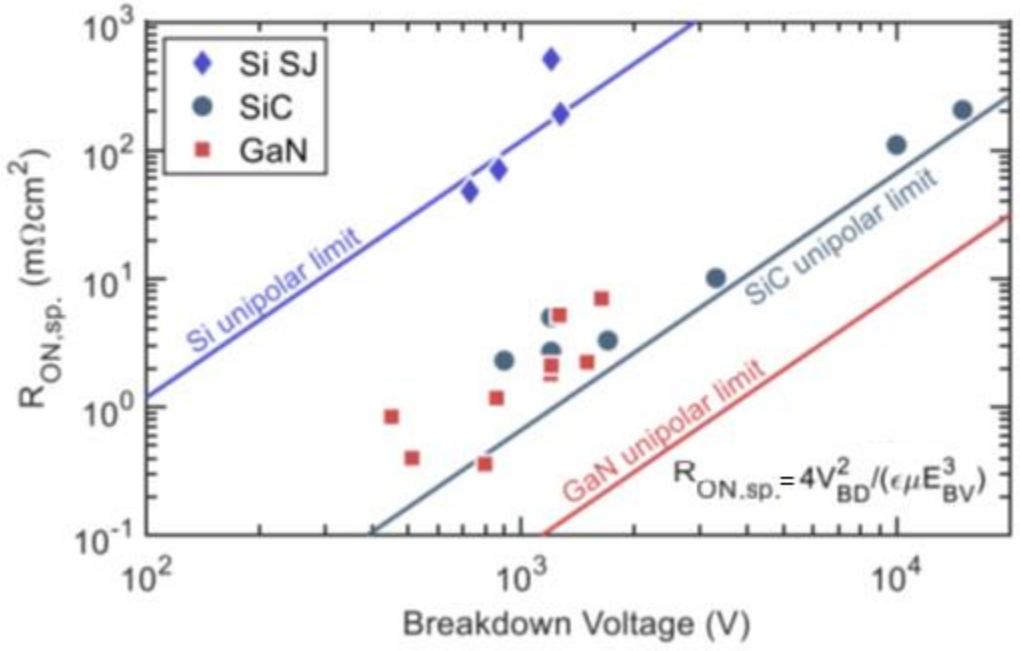
higher critical field enables higher breakdown voltage

Higher carrier saturation velocity enables higher switching frequency

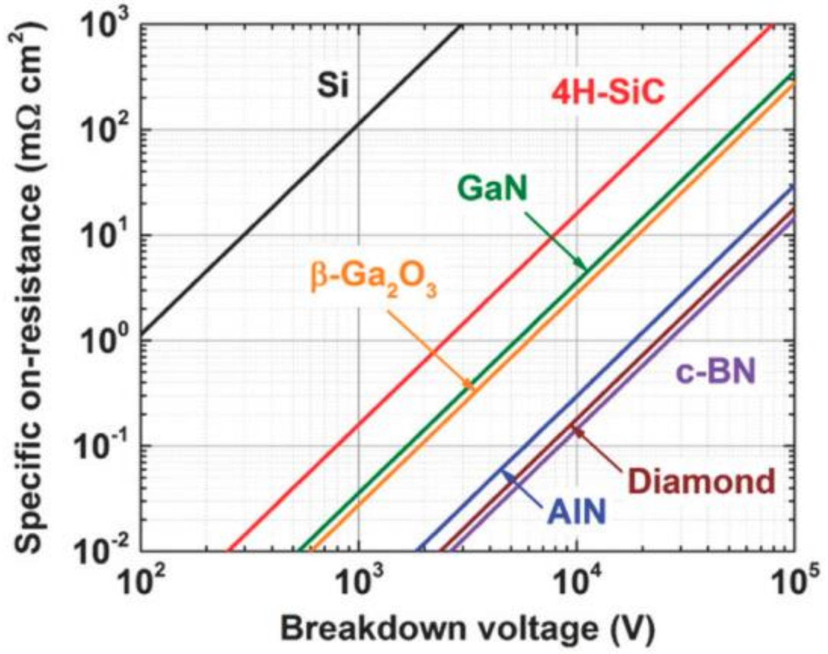
higher electron mobility reduces resistivity and the conduction losses

Why GaN and SiC Devices for Power Electronics?

- SiC was the first mature option to overcome the limits of Si, but:
  - Its relatively poor channel mobility makes it more attractive above 600 V
- GaN can deliver comparable performance with lower cost and easier integration



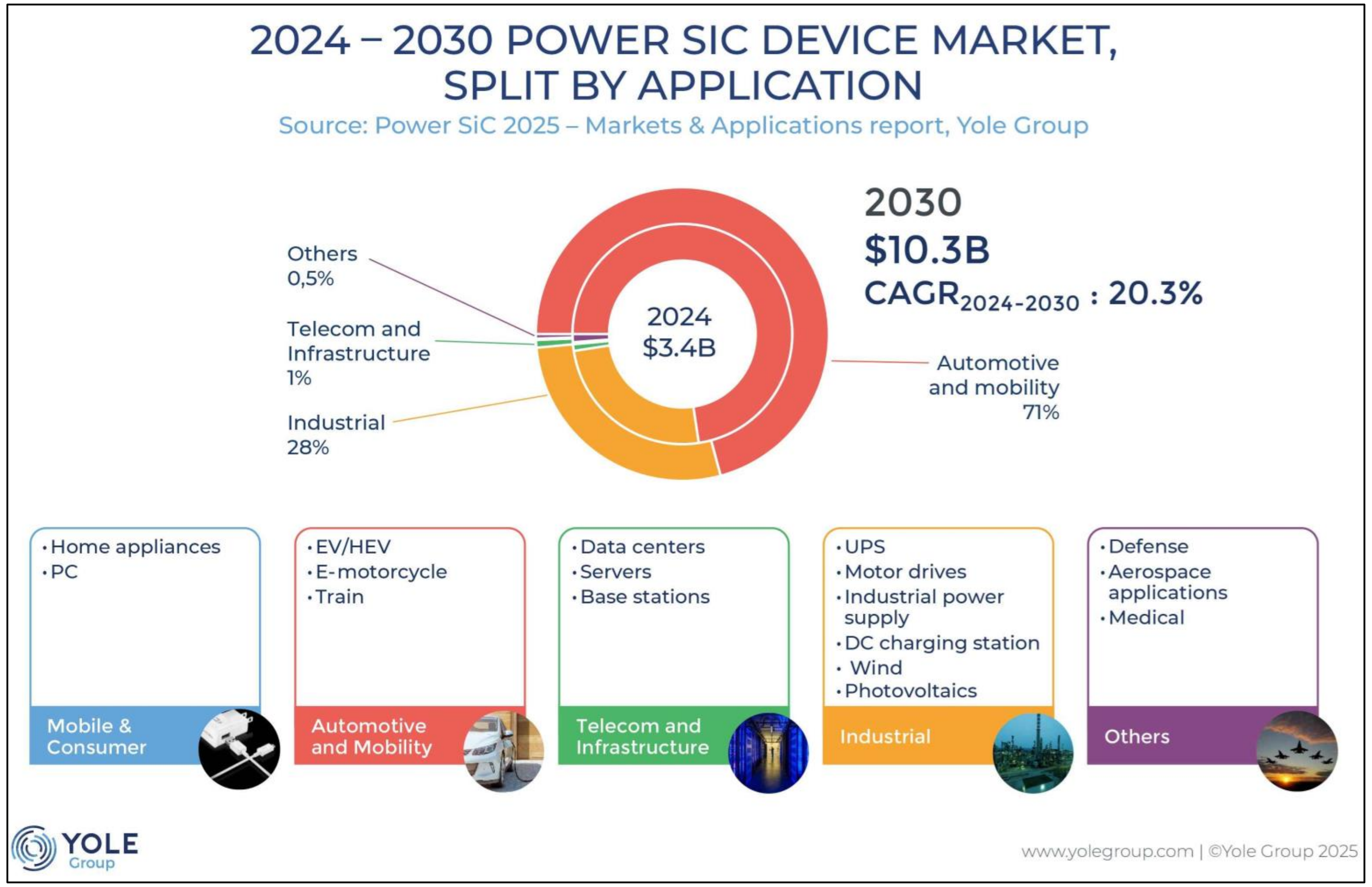
Parameter	Si	GaN	SiC
Band Gap (eV)	1.12	3.39	3.26
Critical Field (MV/cm)	0.23	3.3	2.2
Electron Mobility (cm2/V·s)	1400	1500	950
Thermal Conductivity (W/cm·K)	1.5	1.3	3.8

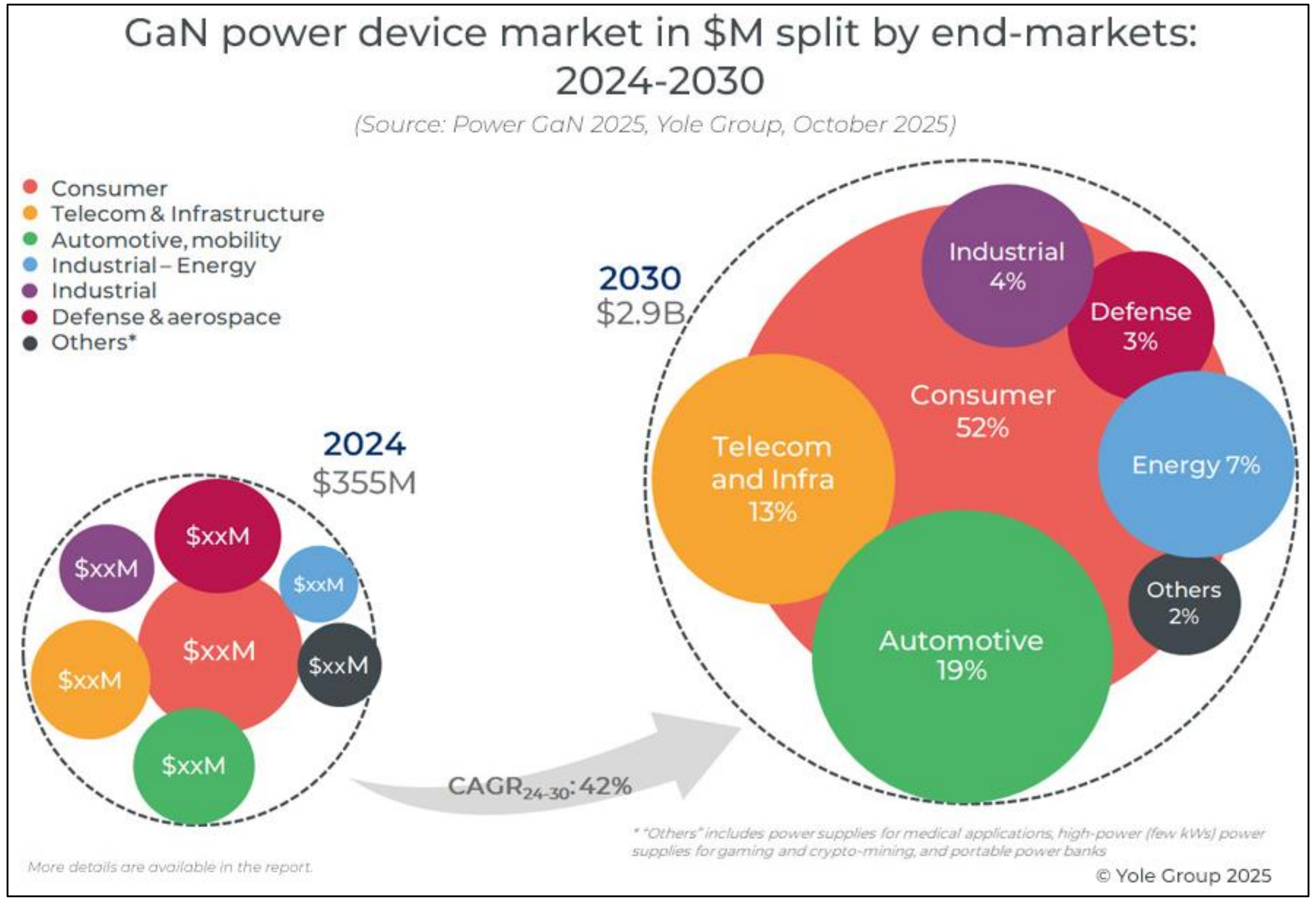


Source: G. Iannaccone et al., *IEEE Access*, vol. 9, 2021, doi: 10.1109/ACCESS.2021.3118897

Source: F. Zhao et al., *MDPI,* 2024, 17, 3437. https://doi.org/10.3390/ma17143437

Power Device Market Forecast: SiC, GaN





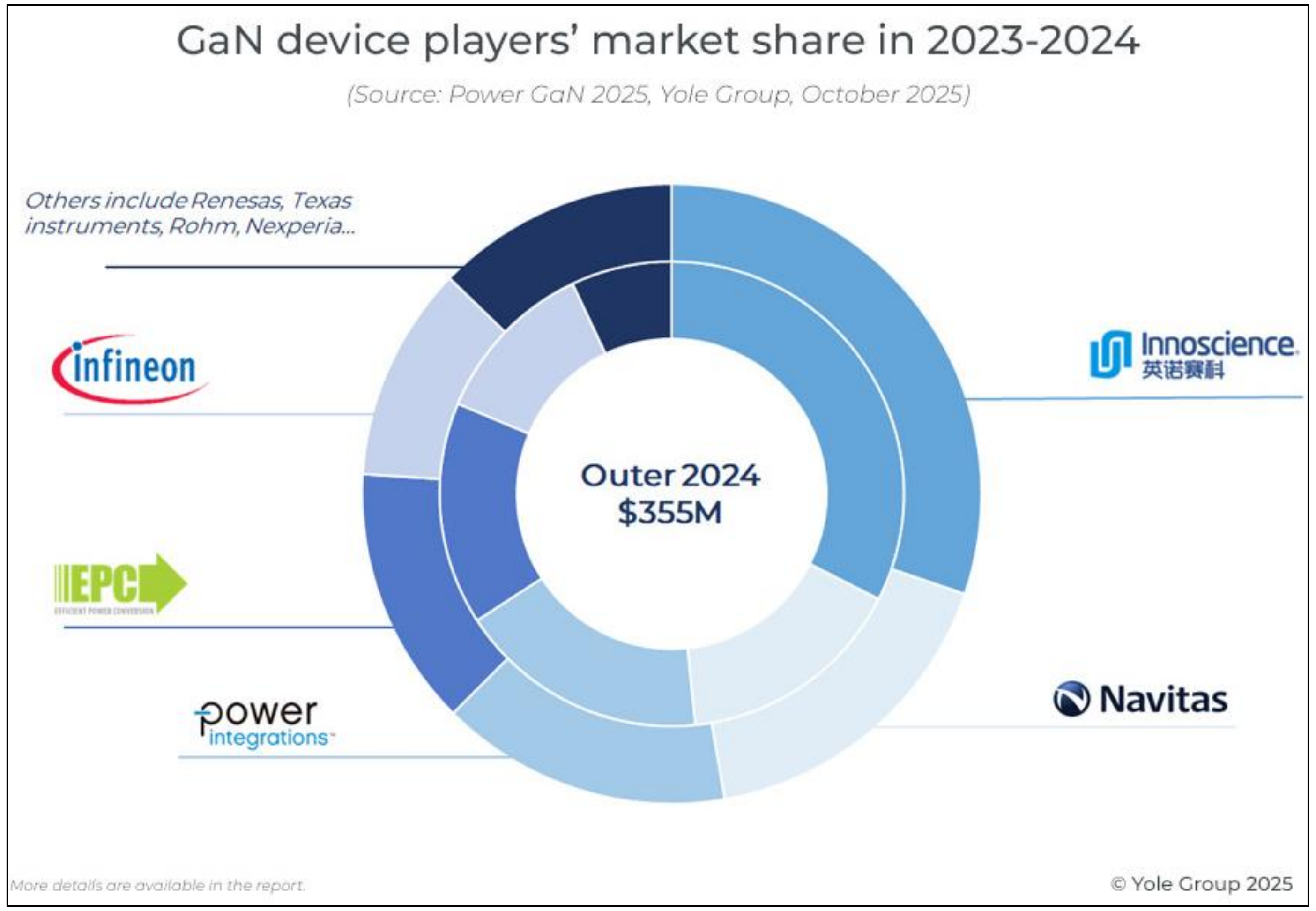
Projected market size by 2030

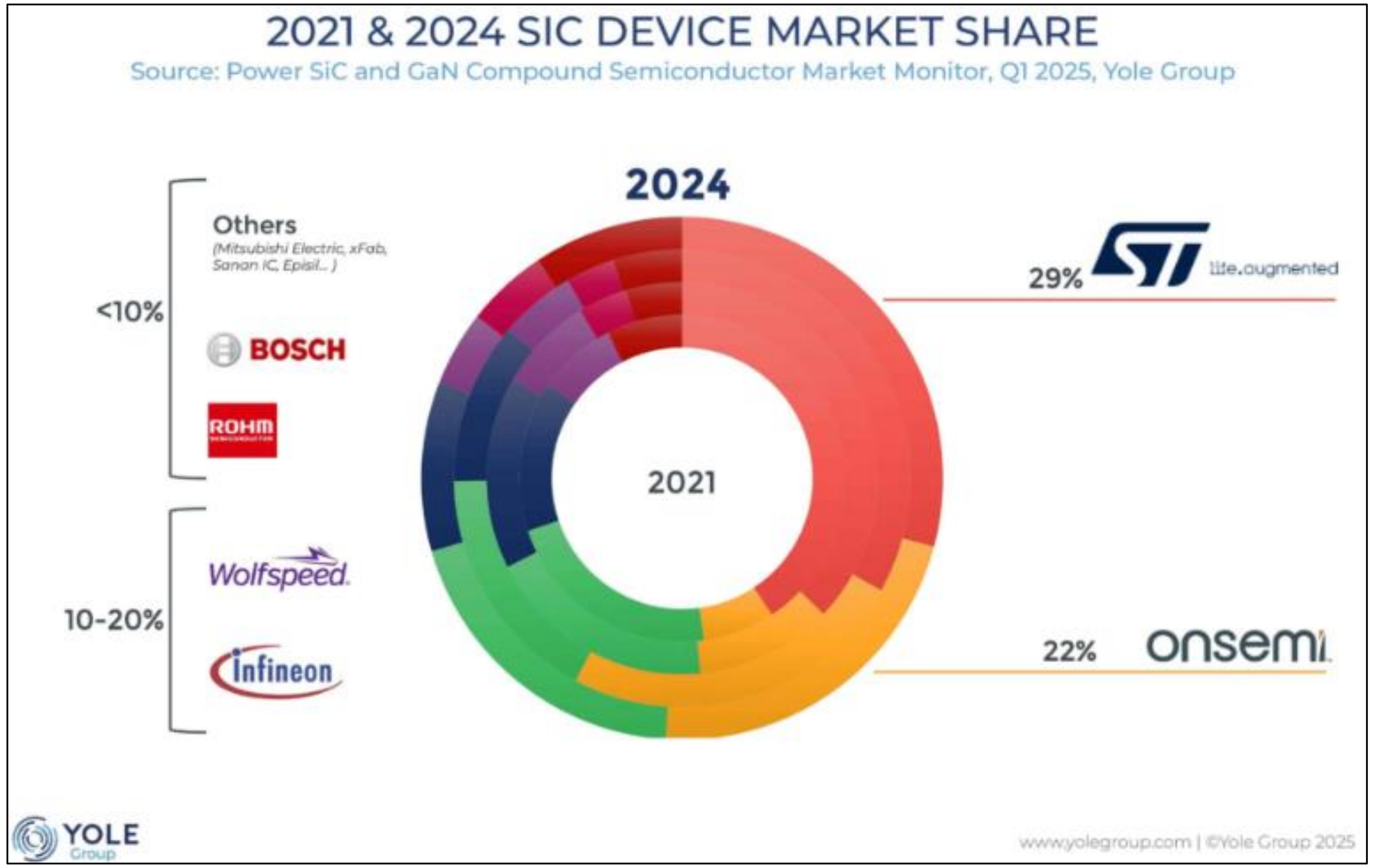
1. Silicon ($ 30.1B)
2. Silicon carbide ($ 10.3B)
3. Gallium nitride ($ 2.9B)

Projected market growth by 2030

1. Gallium nitride (42%)
2. Silicon carbide (20.3%)
3. Silicon (~5%)

GaN & SiC Power Device Players (2024)





- In 2024, the GaN market was led mainly by U.S. and Chinese players
- In contrast, the SiC market showed stronger European leadership

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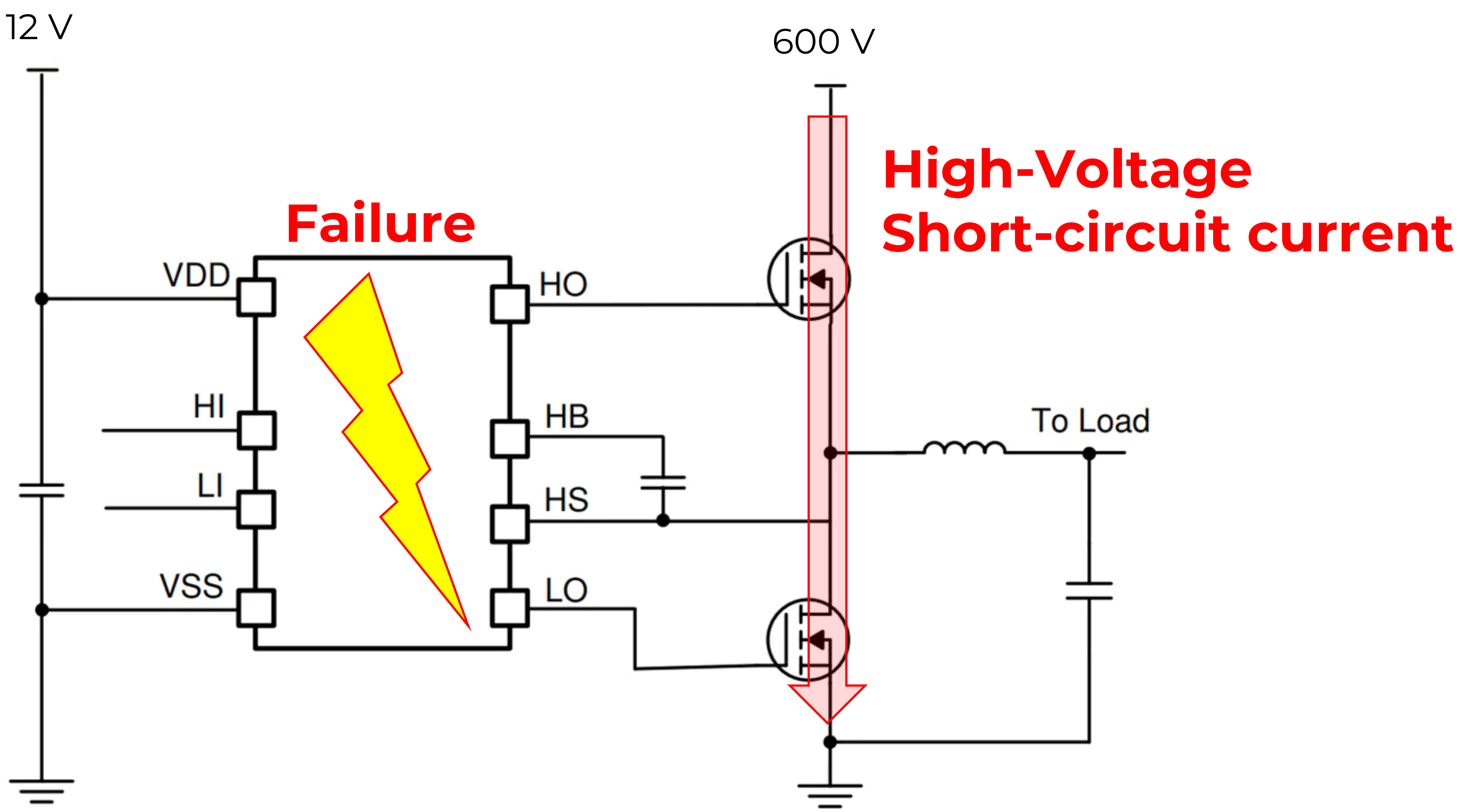
Power Electronics Requires Normally-OFF Devices



- In the event of gate-driver failure, transistors must remain OFF for safe operation

Commercially available GaN Power Transistors

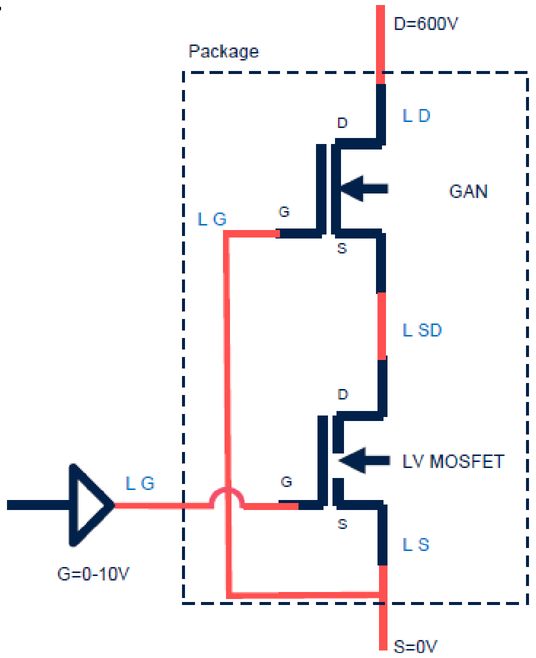
Hybrid approach: HV GaN + LV Si

Pro's

- Normally-on GaN offers low R_{DS}, high BV, good reliability
- Compatible with standard silicon gate drivers already on the market

Con's

- Parasitic inductances introduced during packaging may limit overall performance
- Higher Cost



Monolithic approach

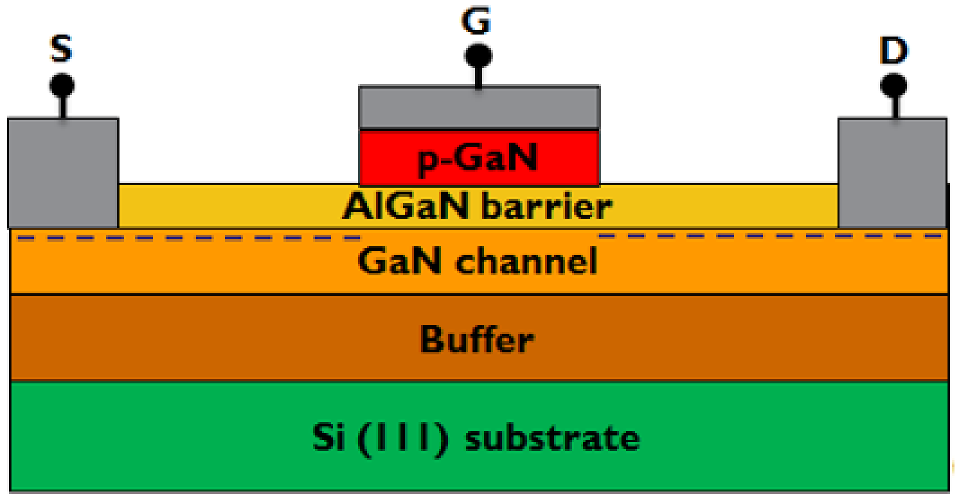
Pro's

- Enable IC integration, support higher switching frequencies, lower cost

Con's

- More complex manufacturing process
- Limited overdrive, reliability

- ***Both are commercially established mainly in the 650 V class***
- ***Only a few vendors offers GaN cascode up to 1200 V (GaN-on-sapphire)***

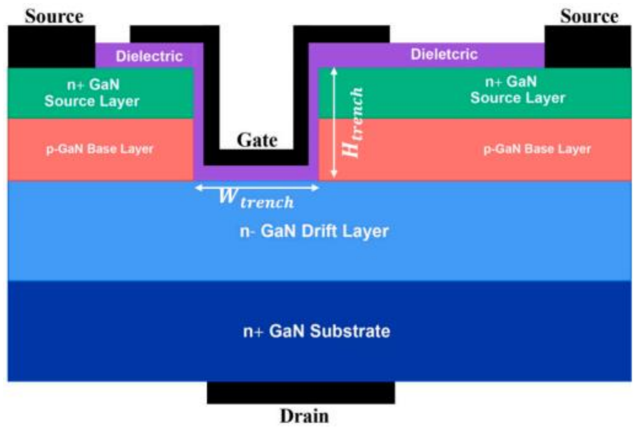


R&D stage: Vertical or Quasi-vertical GaN

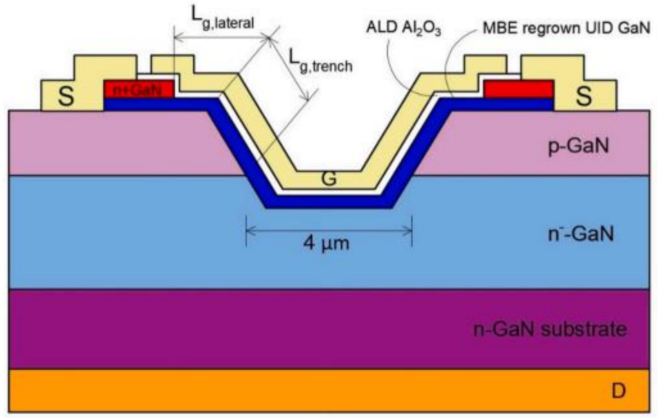
Goal: Higher BV and lower Ron in a smaller chip area

Main Barriers: reliability, cost, material/substrate quality, and process complexity/yield

Vertical

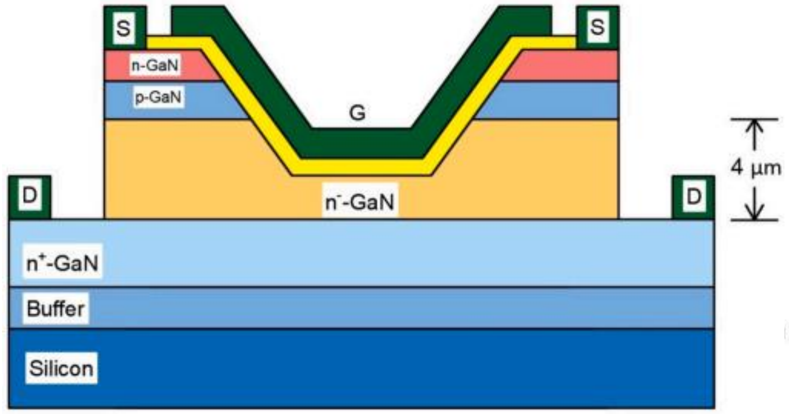


[R. Shankari et al., Microelectron. Eng., Vol. 302, 2026, https://doi.org/10.1016/j.mee.2025.112418.]

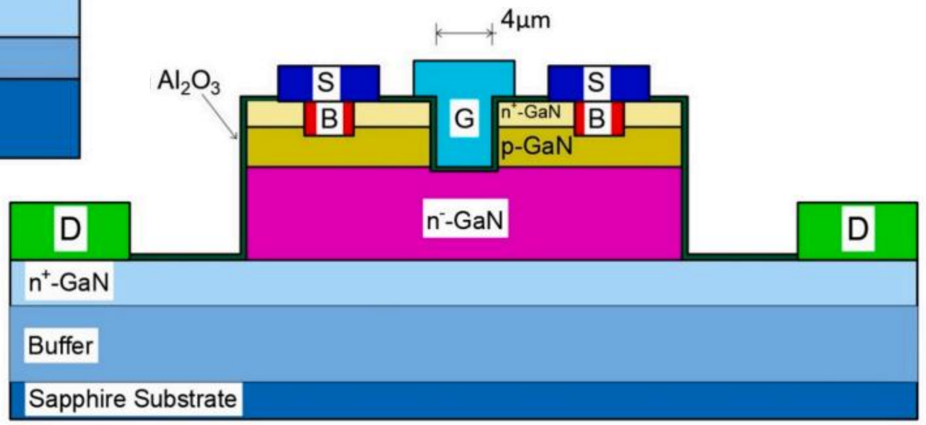


[W. Li et al., *IEEE DRC*, 2017, doi: 10.1109/DRC.2017.7999414]

Quasi-vertical



[C. Liu et al., IEEE EDL, vol. 39, no. 1, 2018, doi: 10.1109/LED.2017.2779445.]



[R. Zhu et al., *IEEE EDL*, vol. 42, no. 7, 2021, doi: 10.1109/LED.2021.3080260]

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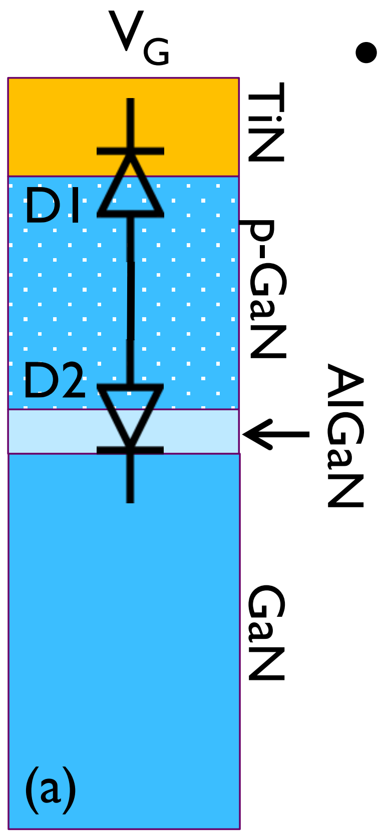
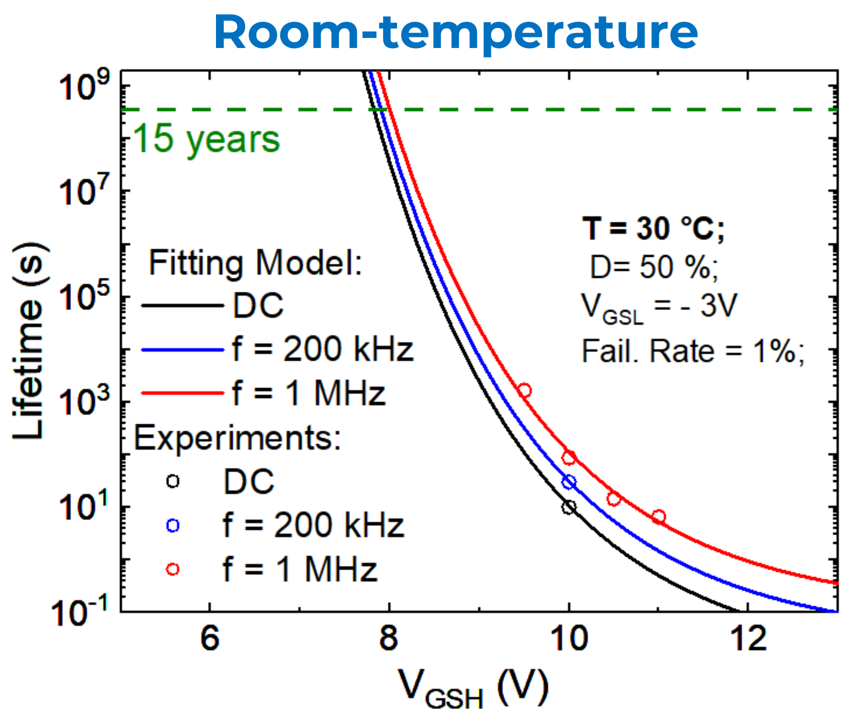
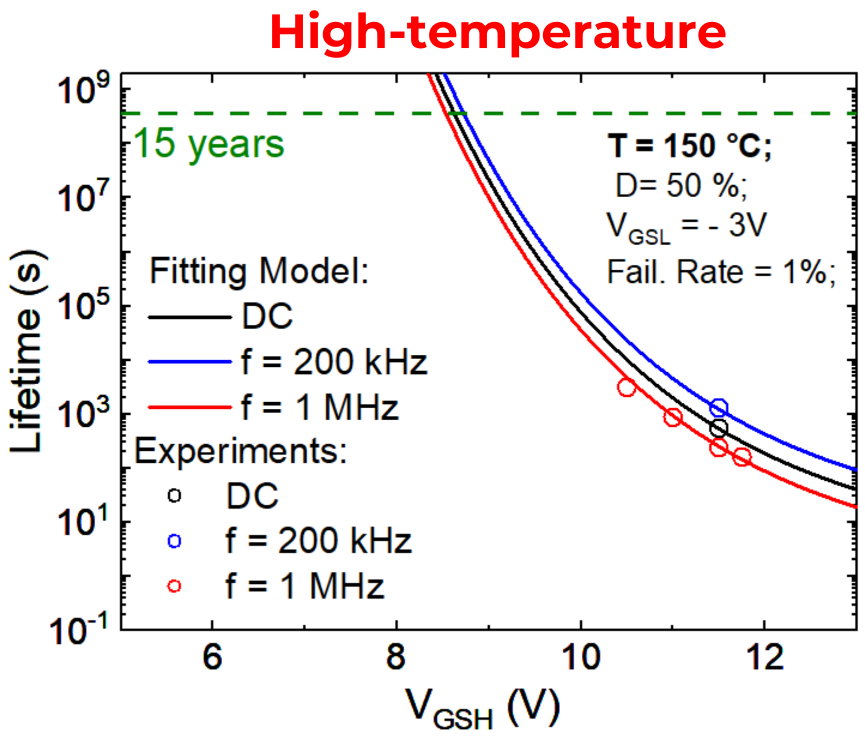
Emerging Technologies: The Need for New Standards and Tests (1)

- **Gate Reliability** in GaN HEMTs differs from that of Si-MOSFET
- DC stress is no longer the worst-case reliability condition (mission profile)
- High switching frequency may activate additional degradation mechanisms





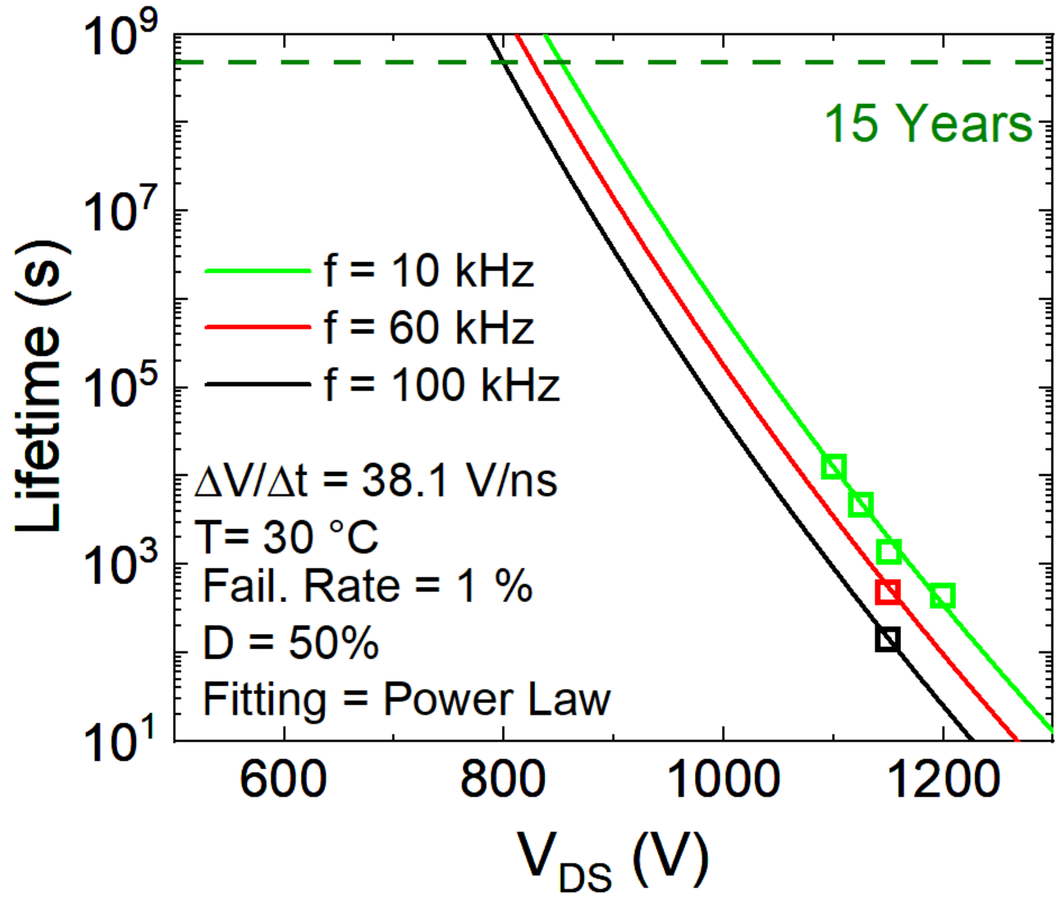


Sources: [M. Millesimo et al., *IEEE T-ED*, Early access, 2026, doi: 10.1109/TED.2026.3664776] – [M. Millesimo et al., *IEEE EDL*, vol. 43, no. 11, pp. 1846-1849, Nov. 2022, doi: 10.1109/LED.2022.3206610] – [M. Millesimo et al., *IEEE IRPS*, 2022, doi: 10.1109/IRPS48227.2022.9764592]

Emerging Technologies: The Need for New Standards and Tests (2)

OFF-state reliability: the combination of high voltage and high frequency accelerates degradation in GaN devices

- Reliability static tests (HTRB) is no longer representative
- Need for dynamic stress test (DRB) and models



$$Lifetime(V,T,f) = TTF_0\left(\frac{V}{V_0}\right)^{-n} exp\left(\frac{E_a}{k_B}\left[\frac{1}{T_K}-\frac{1}{T_{0K}}\right]\right) exp(-\alpha(f-f_0))$$

Sources: [M. Millesimo et al., "Lifetime modeling of Schottky p-GaN Gate HEMTs under Dynamic Stress Tests", *IEEE TPEL*, under review, 2026]

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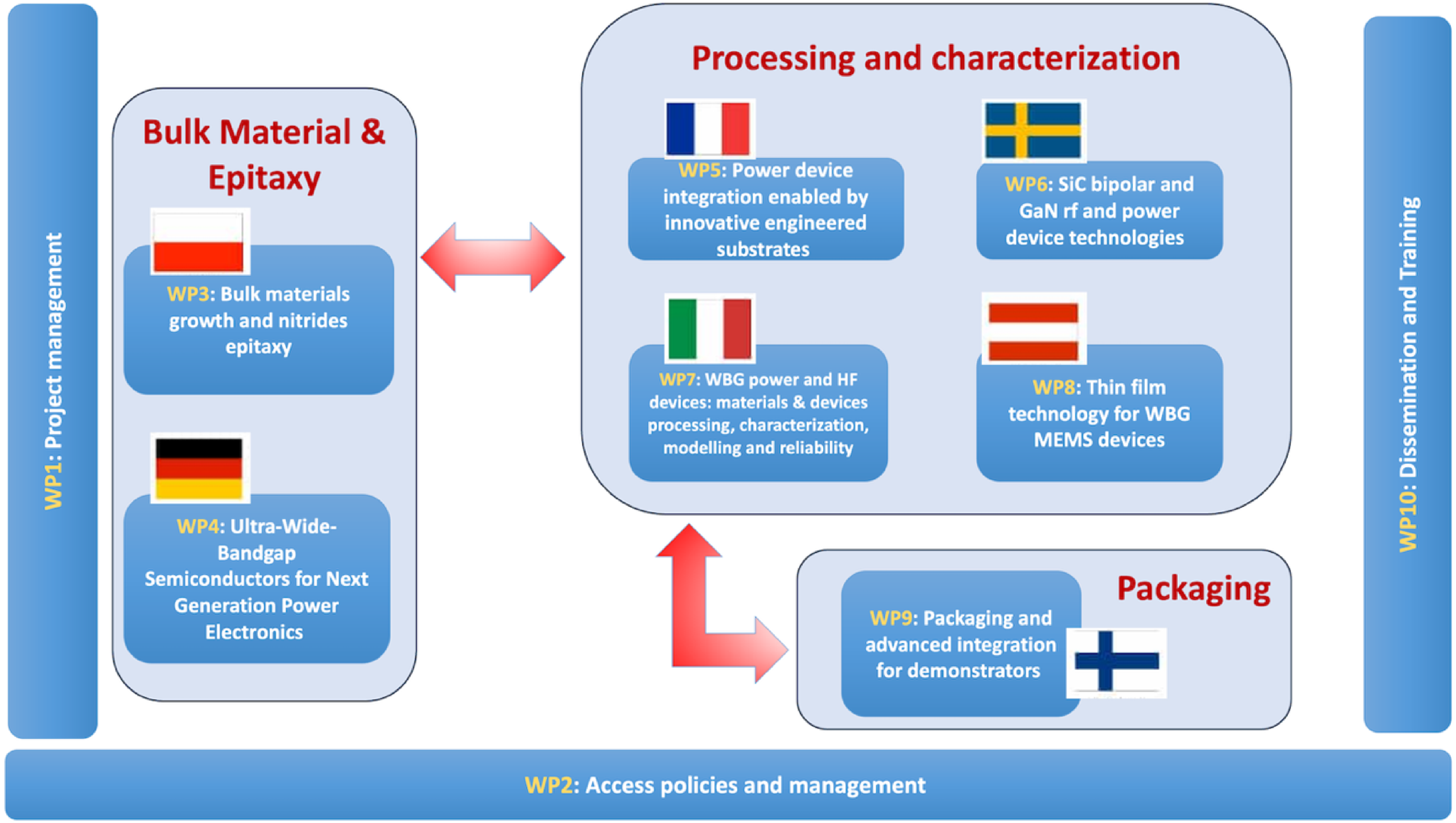
The Wide BandGap (WBG) Pilot Line

WBG Wide Band Gap
future power electronics

- **One** of the **five pilot lines** launched under the **Chips for Europe Initiative**
- Coordinated by the **Italian** National Research Council (CNR-IMM)
- Focused on the **development** and **industrialization** of **WBG semiconductors,** including **SiC** and **GaN**
- A **5-year, €360 million** project involving **15 partners** across **7 EU countries,** with most of the investment allocated to the construction of a **new laboratory in Catania** (Italy)
- Aims to **bridge the gap** between **lab. research** and **industrial manufacturing**
- A strategic initiative to strengthen **Europe's technological autonomy in semiconductors**

WBG Pilot Line Project



- From materials
- to device processing and characterization
- including packaging

WBG Pilot Line Activities

	Material Growth & EPI	Device Processing	MEMS and detectors Processing	Advance char. and Reliability	M&S - PDK	Packaging & Integration
SiC	CNR	CNR, KTH	FBK	IUNET, KTH	I&C	FBK
GaN	IHPP, CNR, LUND	CNR, IMiF, CHAL		IUNET, IMiF, CHALM	I&C	
Ga_2O_3	LUND	IMiF, CNR		IUNET, IMiF	I&C	
AlN	LIU	CHALM	FBK	IUNET	I&C	
Diamond				IUNET	I&C	

- Multiple materials
- Different technology levels

WBG Pilot Line: Power Devices

WBG Wide Band Gap
future power electronics

	RF devices Lateral	Power Lateral devices unipolar	Vertical devices unipolar	BJT
SiC			CNR	KTH
GaN	CNR CHAL	CNR CHAL IMiF	CNR IMiF	
Ga_2O_3			CNR IMiF	
AlN	CHAL	LUND		

Materials	Processing	Devices	Applications
ST life.augmented	ASM	ST life.augmented	Valeo
SiCrystal A ROHM Group Company	AIXTRON	infineon	
soitec	APPLIED MATERIALS	onsemi	
KISAB	axcelis	NXP	
OMMIC innovating with III-V'S	COHERENT	STLAB	
		SENSIC	

- Different materials and technologies
- Industrial stakeholders that have expressed interest

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General conclusions

- GaN and SiC are complementary WBG technologies for next-generation power electronics
- GaN-on-Si lateral normally-OFF devices are currently among the most relevant solutions up to ~650 V
- Dedicated reliability models and test methods are needed to properly qualify WBG devices under realistic operating conditions
- Further advances are still required for higher-voltage GaN and for UWBG-based power devices
- Pilot-line initiative is crucial to accelerate the transfer of WBG technologies from lab to industry

The EU-Japan Digital Week is an initiative under the EU-Japan Digital Partnership and is supported by the following projects and organisations