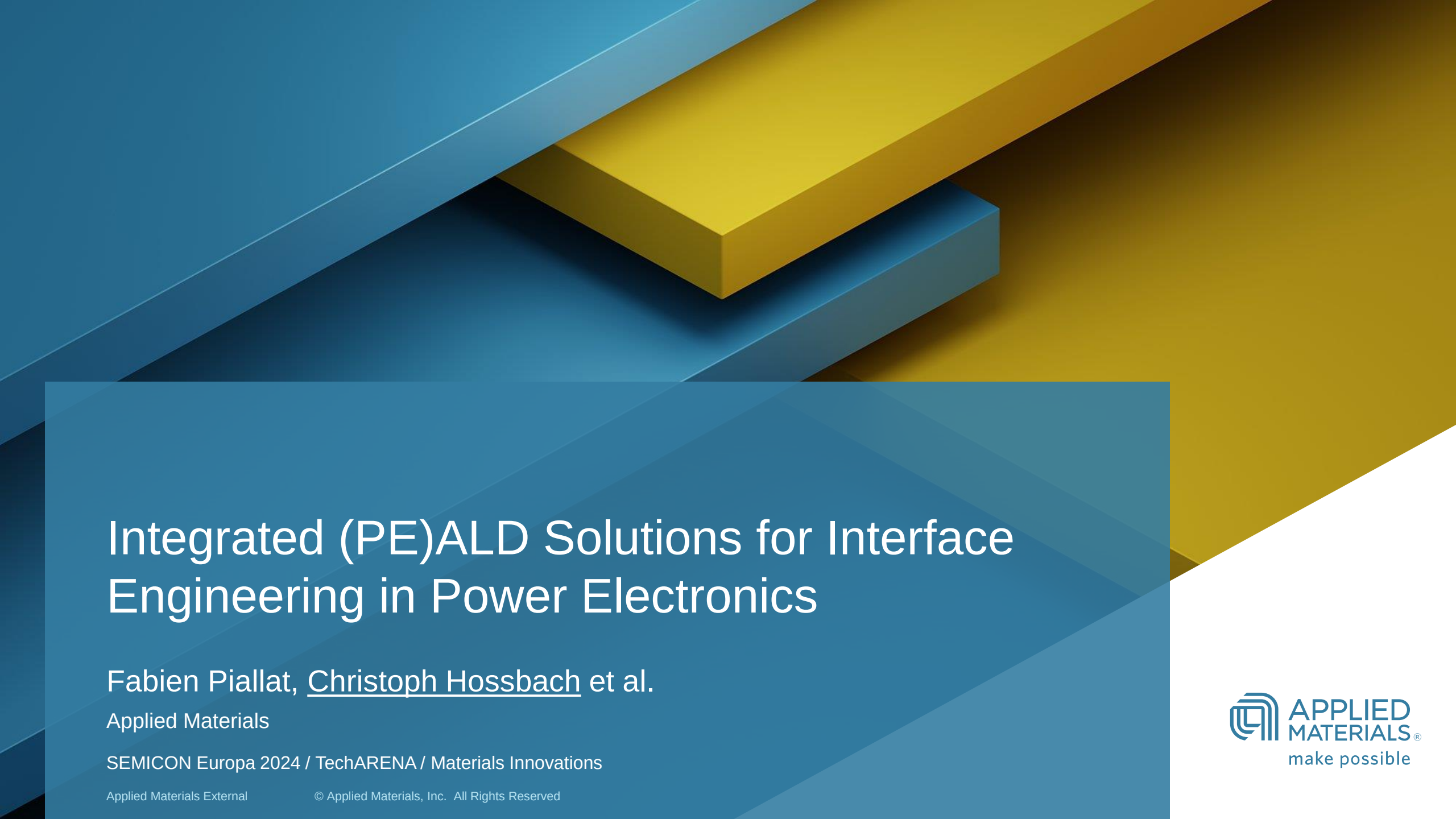




Integrated (PE)ALD Solutions for Interface Engineering in Power Electronics

Fabien Piallat, Christoph Hossbach et al.

Applied Materials

SEMICON Europa 2024 / TechARENA / Materials Innovations

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SiC & GaN markets

ALD and material integration

SiC

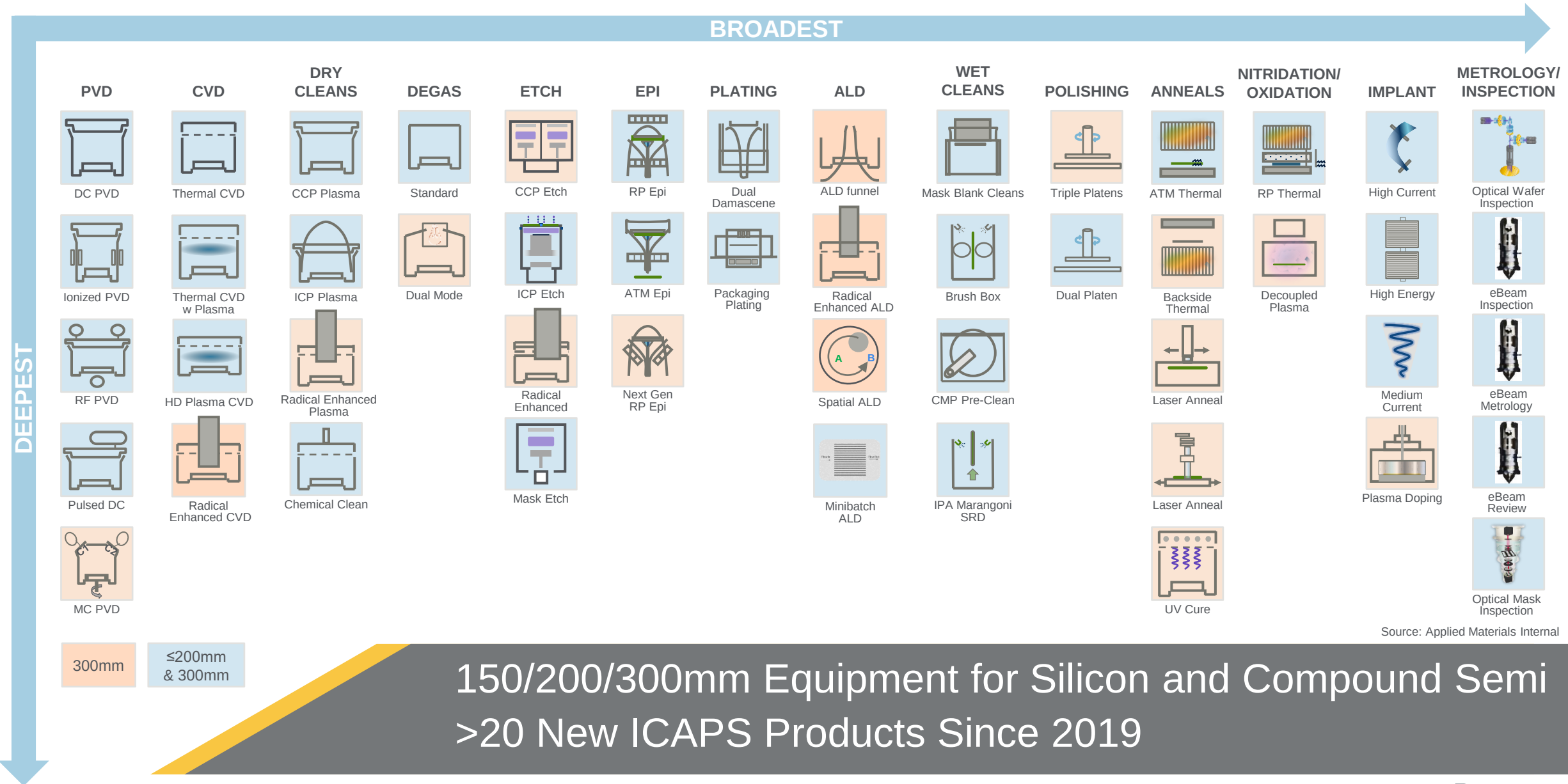
- Inflection and application of ALD
- Results with Applied™ Morpher™

GaN

- Inflection and application of ALD
- Results with Applied™ Morpher™

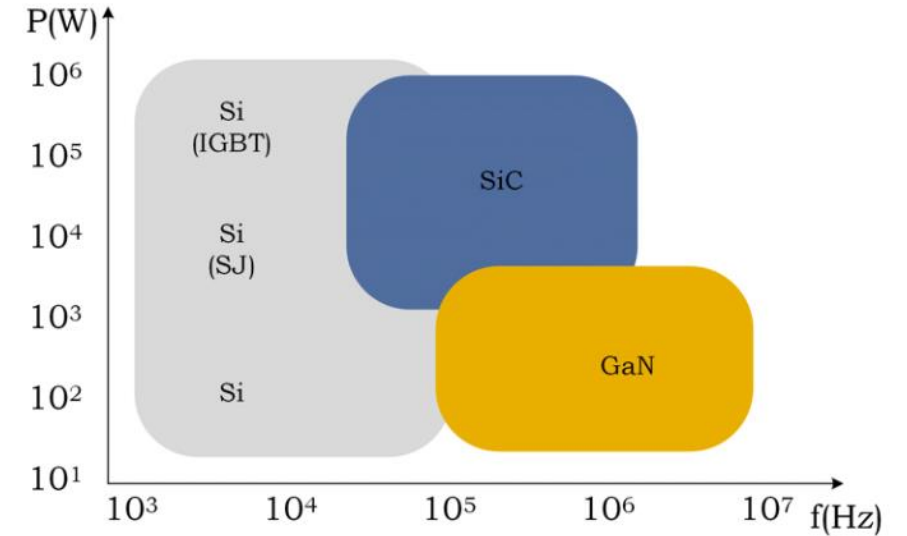
Outlook

SiC & GaN markets: serving w/ broadest semiconductor equipment portfolio



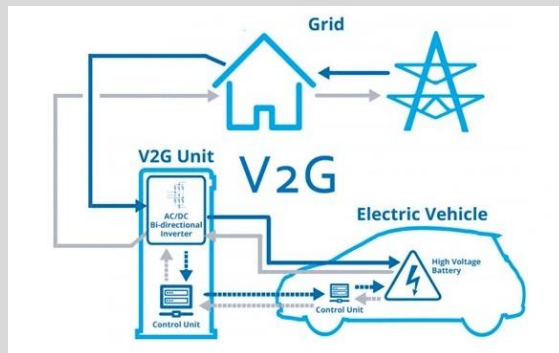
SiC & GaN markets: for Green semiconductor applications

- In grand scheme of electrification / decarbonization of everything SiC and GaN technologies are playing a key role to improve systems efficiency
 - » SiC at the high power and mid frequency
 - » GaN at the low power and high frequency



SiC Use Case Example:

Electrical Vehicle Power management



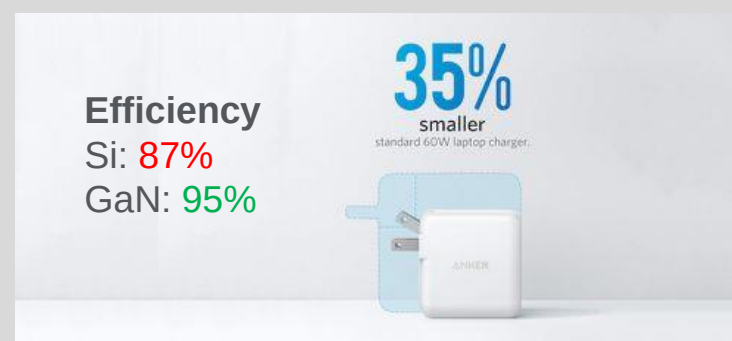
DC → DC, DC → AC

(Conversion, Switching, Energy recovery, traction inverter, on-board charger)

Source: Applied Materials Internal

GaN Use Case Example:

Consumer Device Charger (Converter)



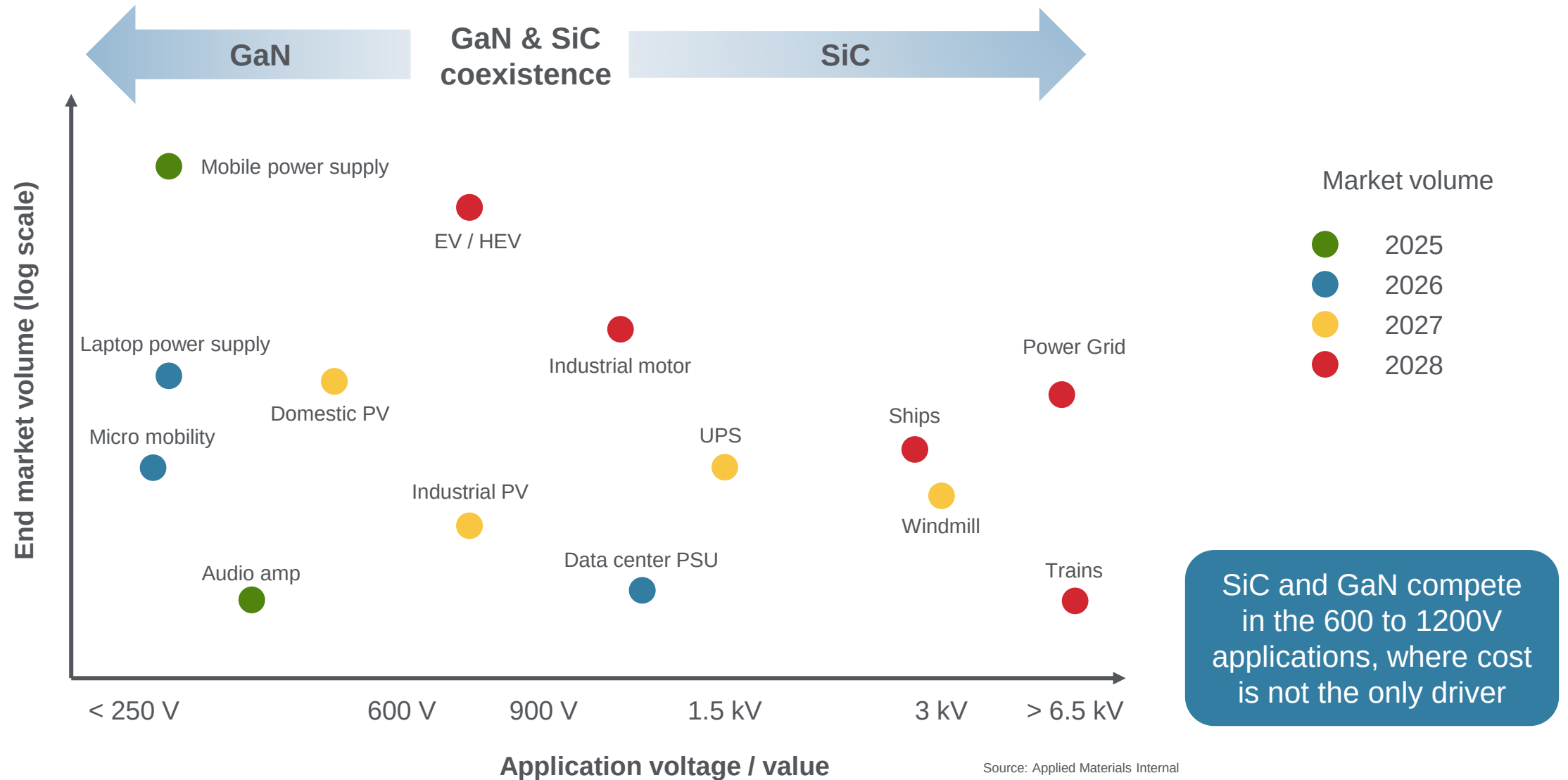
A better charger

(More efficient, less heating, Higher Power Density, less elements, multipurpose)

Source: Applied Materials Internal

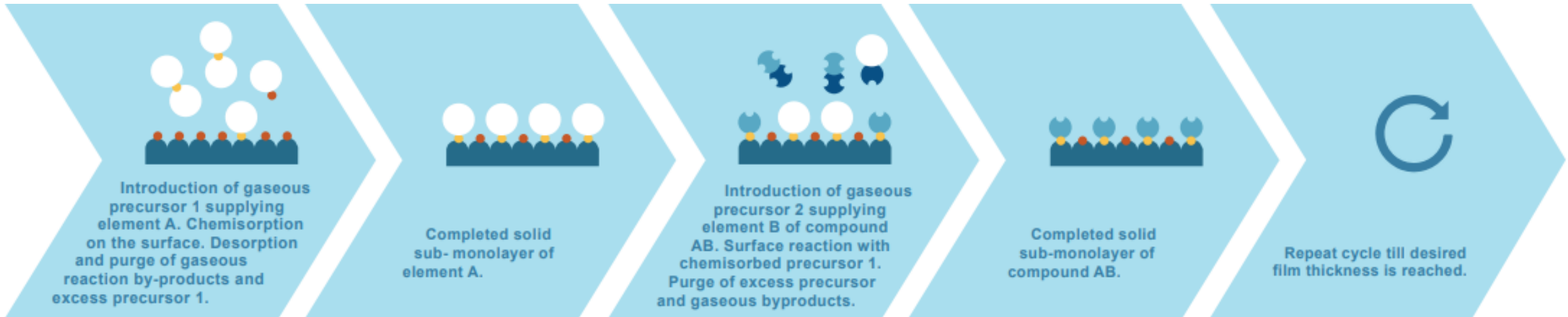
Both SiC and GaN drive further world's energy efficiency & decarbonization

SiC & GaN markets: Predicted applications



ALD and Material Integration: What is ALD?

- ALD is an advanced deposition technique
- Belongs to family of chemical vapor deposition (CVD)
- ALD is based on sequential well-separated chemical surface reactions



Source: Applied Materials Internal

- Repeat ALD cycle until desired film thickness achieved. Typical growth per cycle 0.1 to 2 Å.
- ALD grows films with extreme high conformality, uniformity and film thickness control on virtually all surfaces and 3D structures

Atomic Layer Deposition is based on surface enhanced chemical reaction

ALD and Material Integration: How can ALD help SiC and GaN?

- Surface / interface control at the atomistic level

Surface-controlled deposition



Source: Applied Materials Internal

- Extremely conformal

Surface-controlled deposition

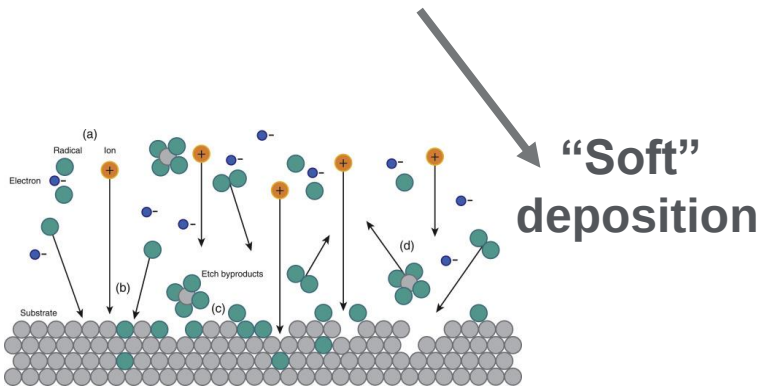


Source: Applied Materials Internal

- Low temperature compared to CVD

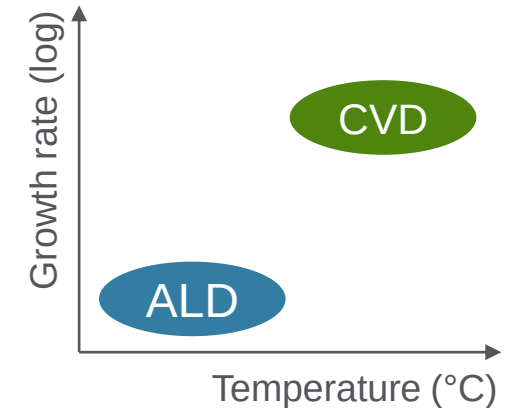
- Low damage compared to PVD

“Soft” deposition



Source: H. Ekinici, Plasma and Reactive Ion Etching, Elsevier, 2016, ISBN 9780128035818

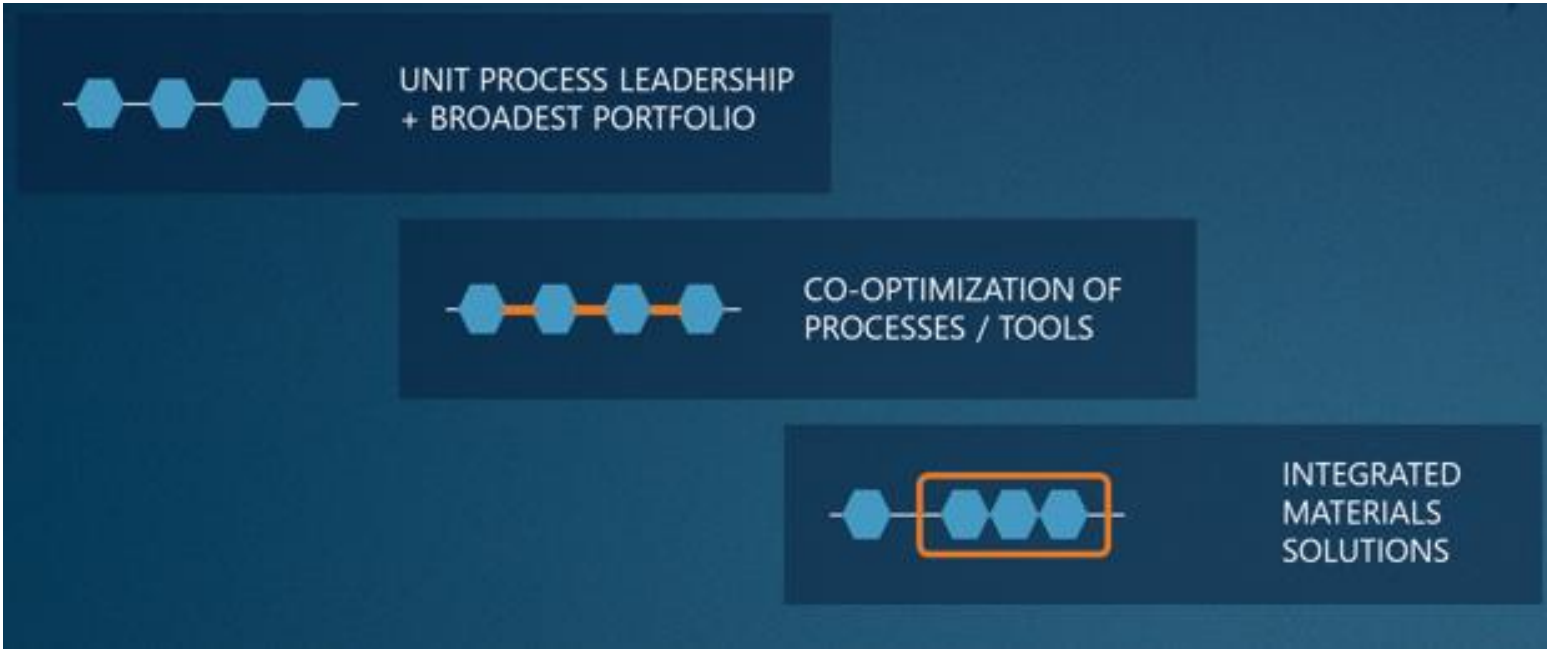
ALD is a “gentle” deposition technique, ideal for surface/interface engineering



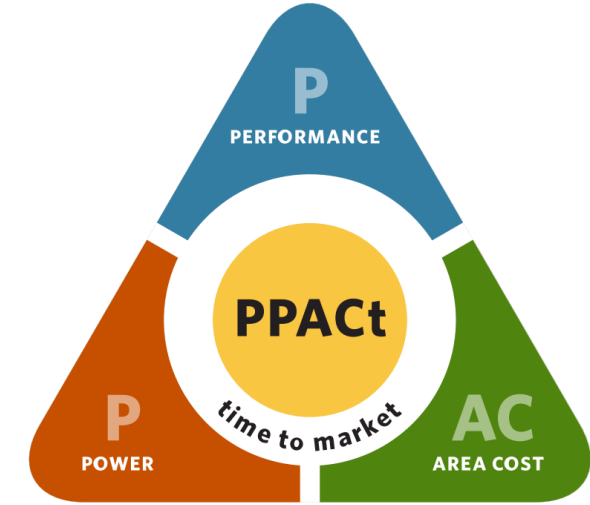
Source: Applied Materials Internal

ALD and Material Integration: Integrated Materials Solutions

Faster Time to Market, Higher Value



Integrated solutions allow
ideal control of the interfaces and contaminations



Value to Customers:

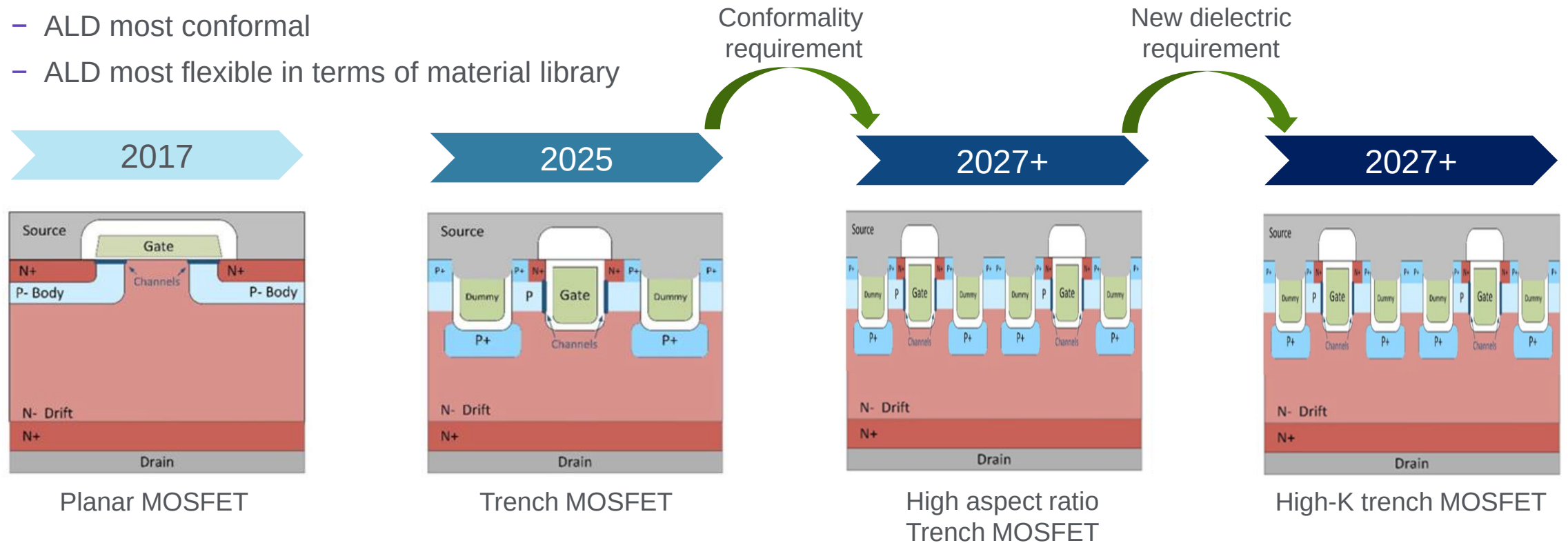
- More complete solutions
- Direct process to PPAct connection
- Higher value to customer
- Pre-FAB qualifications
- Faster time to market
- Differentiated modules
- Device-level collaboration

Image source: Applied Materials Internal

SiC: Inflections Enabled by ALD

■ SiC inflection

- » Thermal grown oxide works fine for planar and Super Junction SiC devices
 - But is limited in interface control due to carbon trapping (when transforming SiC to SiO₂)
- » Deposited oxide a must for trench SiC
 - ALD most conformal
 - ALD most flexible in terms of material library

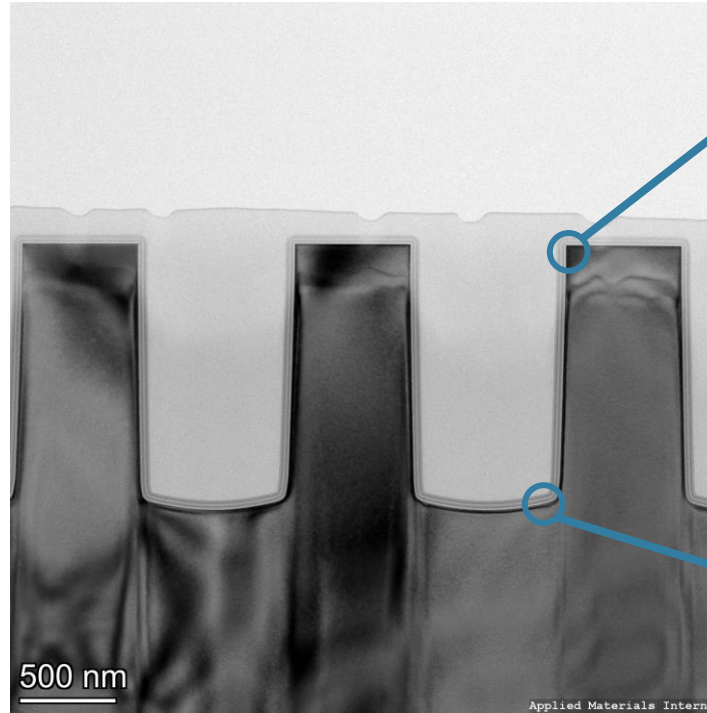


ALD can enable future architectural changes

Image Sources: Applied Materials Internal

SiC: Selected Applied™ Morpher™ Achievements

- Throughput-optimized process results:
 - » >96% conformality on 2:1 aspect ratio (SiC)
 - » >90% conformality on 20:1 aspect ratio (Si)
- Highly-conformal ALD single layers and nanolaminates enable wide range of possibilities in device engineering



Conformal deposition of nanolaminate on trench
10nm SiO₂ / 10nm Al₂O₃ / 10nm SiO₂ / 10nm Al₂O₃ / 10nm SiO₂

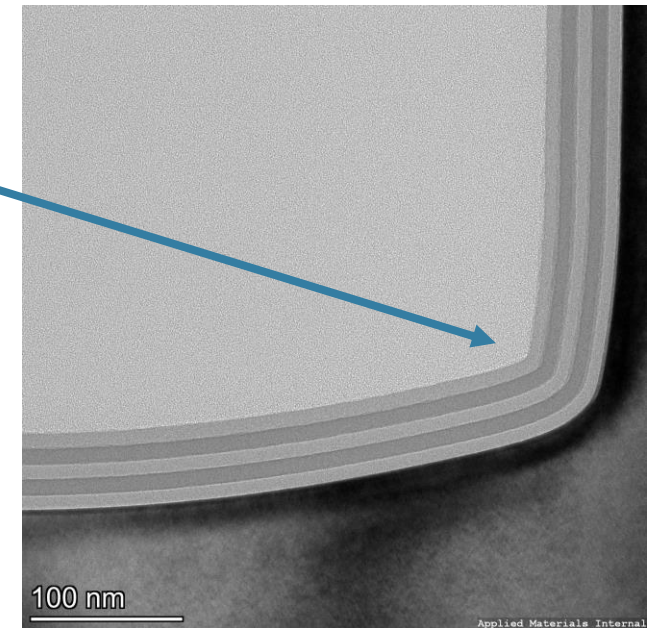
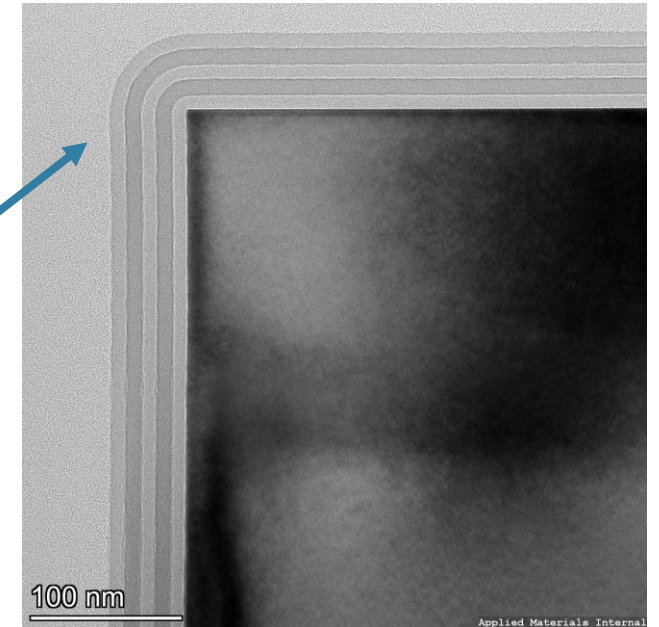


Image sources: Applied Materials Internal

- Conformal deposition validated
- Multiple materials ALD in-situ in same process / reaction chamber

SiC: Selected AppliedTM MorpherTM Achievements

Wide library of materials for added flexibility

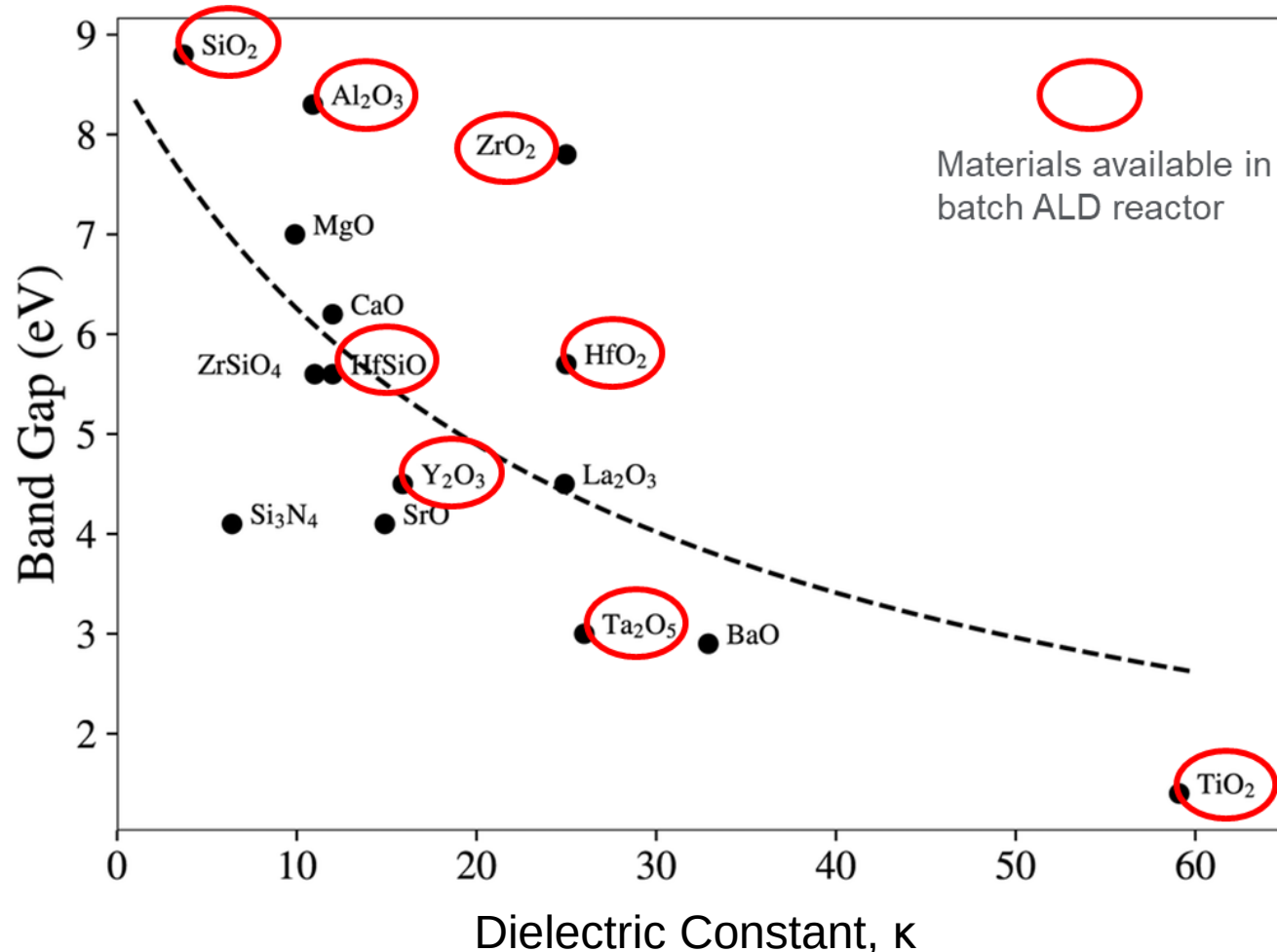


Image modified. Source: Troughton et al, J.Mat.Chem. C, 7(40), 12388-12414.

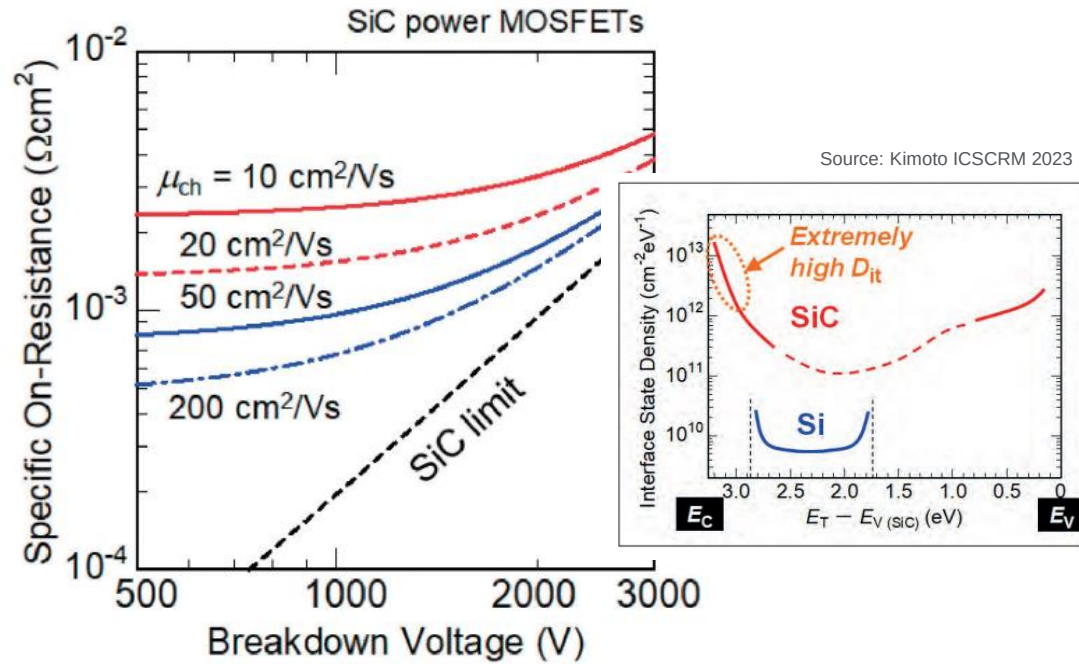
Films can be combined in nanolaminates

Single layer thicknesses down to mono-layer range possible

Ultra conformal and uniform

SiC: Selected Applied™ Morpher™ & Centura™ Achievements

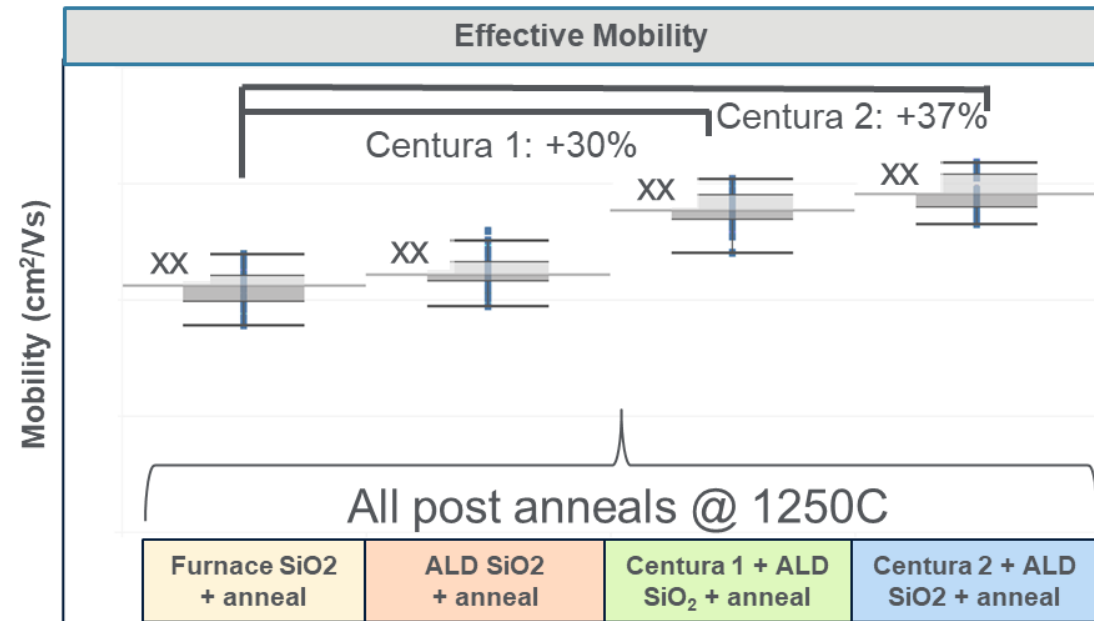
Problem



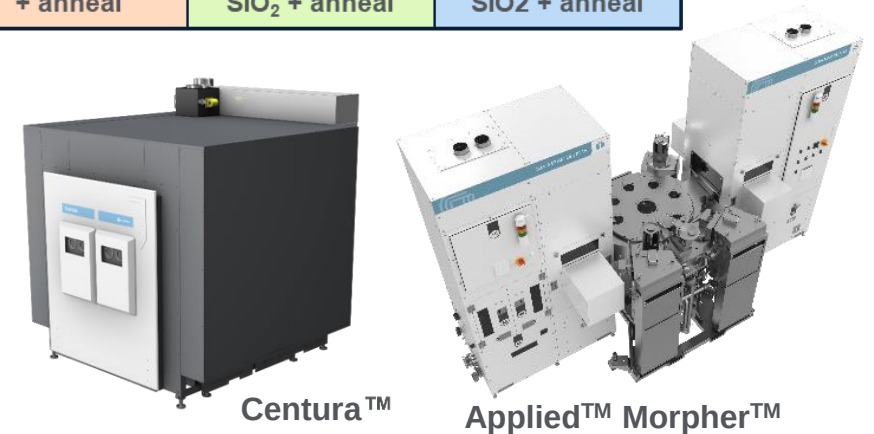
Source: Kimoto et al., Proc. Jpn. Acad., Ser. B 98 (2022)

- High D_{it} at SiC/SiO₂ interface is one of the main causes of low mobility
- Co-optimized gate tool process shows enhanced SiC channel mobility avoiding furnace oxidation that causes high D_{it}
- Ready for demo

Mobility Enhancement w/ Applied™ IMS Cluster tool

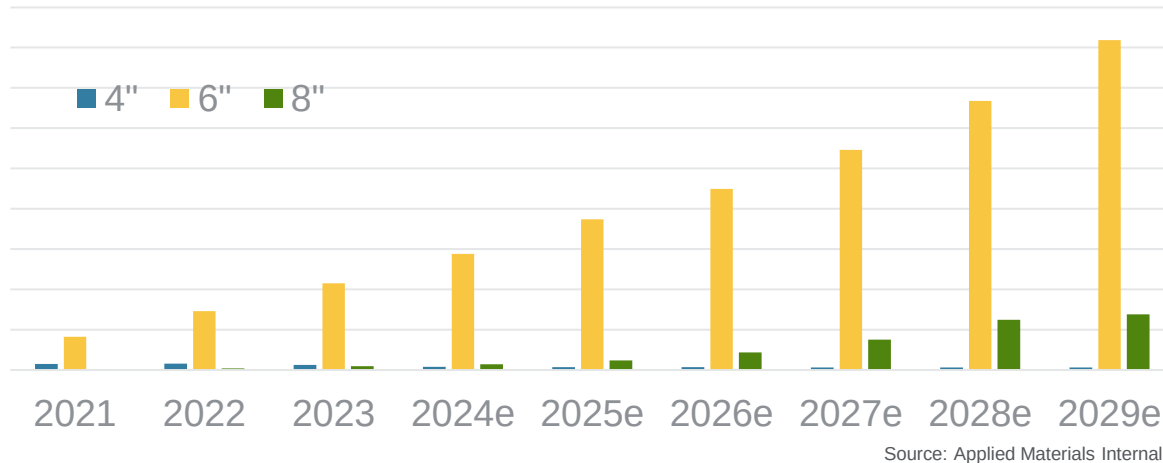


Source: Applied Materials Internal

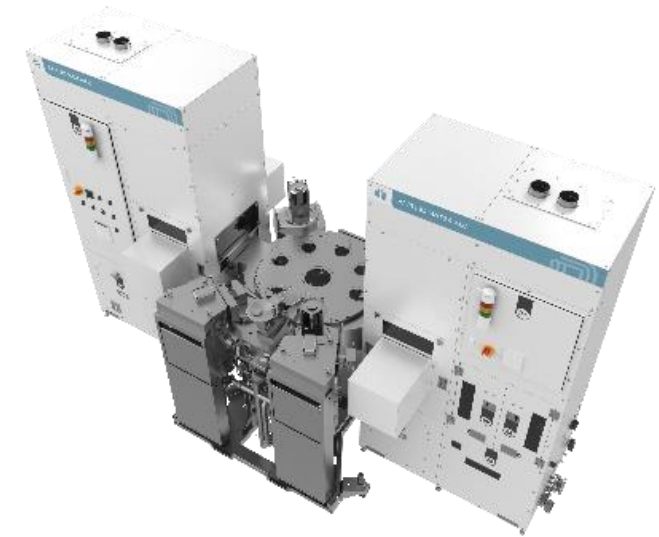
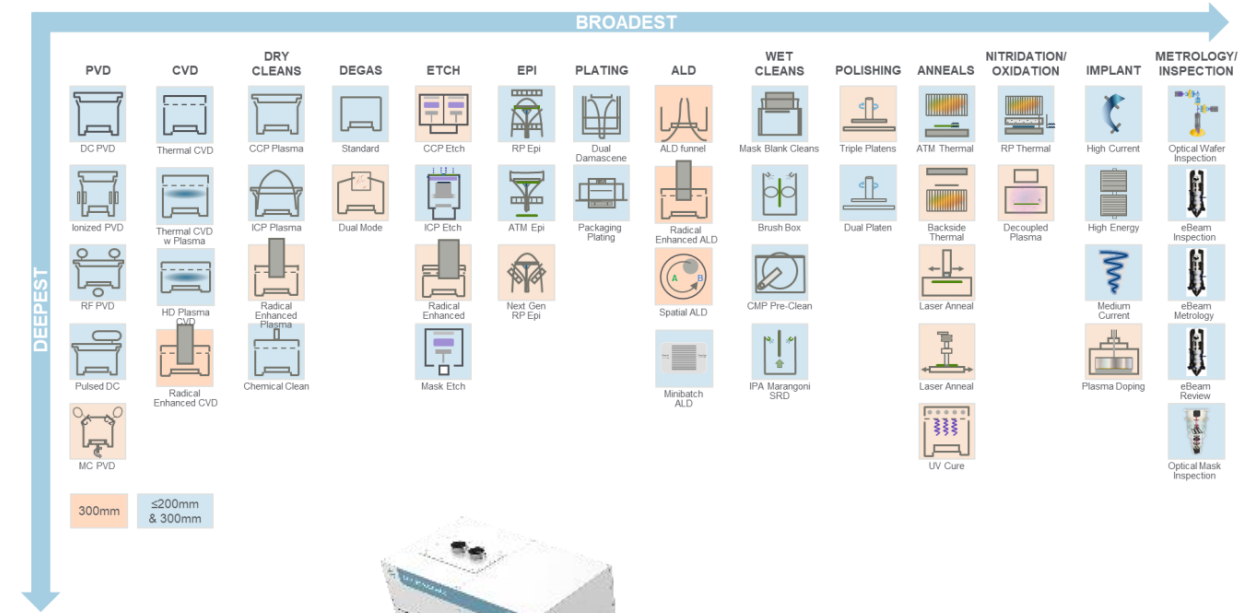


Outlook: Roadmap SiC wafer size

Wafer size market evolution (in total surface area)



- ALD enables inflections in SiC
 - » Conformality needed for trench architecture
 - » High-k needed to extend devices end applications
 - » Future-proof solution
- ALD readily available for 4", 6" and 8" with Applied™ Morpher™
 - » Mini-batch ALD solution – 25 wafers
 - » Easy tool reconfiguration by standard process kit change
 - » Supporting current SiO₂ dielectric, but also future high-k integration

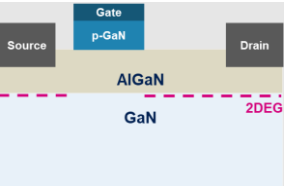


Applied™ Morpher™ Batch ALD cluster

GaN: Inflections enabled by ALD

Gupta et al. Physica Status Solidi 219 (2022)

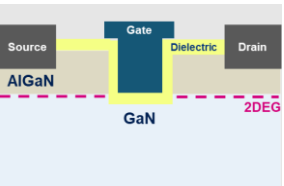
Source: Applied Materials Internal



Planar

2019

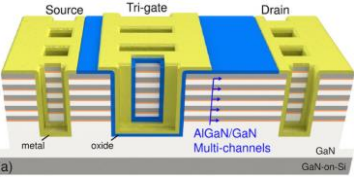
Source: Applied Materials Internal



Gate recess

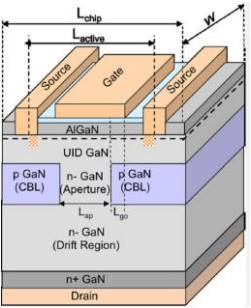
2023

Ma et al. APL 113 (2018)



Nano channel

2026+



Vertical

2028+

Architecture	Planar	Gate recess	Nano channel	Vertical
	Normally on	Normally off	High density	High voltage
Die surface		↓	↓↓↓	
Efficiency		↑	↑↑↑	↑↑↑↑

D-mode HEMTs

- ALD layer in d-mode HEMTs serves as gate dielectric
» $\text{Al}_2\text{O}_3 + \text{SiO}_2$ stack
- ALD layer in Schottky barrier diodes serves as gated edge termination layer

Integrated MIM cap

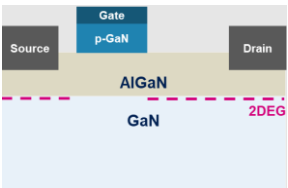
- ALD dielectric and metal layers can also be applied in MIM capacitors
» Metals: ALD TiN, ALD Ru
» Oxides: ALD SiO_2 , ALD Al_2O_3 , ALD HfO_2

ALD can enable future architectural changes

GaN: Inflections enabled by ALD

Gupta et al. Physica Status Solidi 219 (2022)

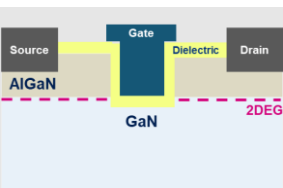
Source: Applied Materials Internal



Planar

2019

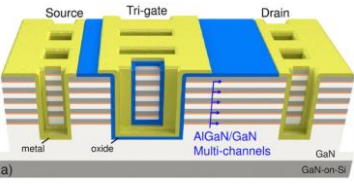
Source: Applied Materials Internal



Gate recess

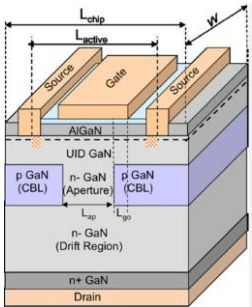
2023

Ma et al. APL 113 (2018)



Nano channel

2026+



Vertical

2028+

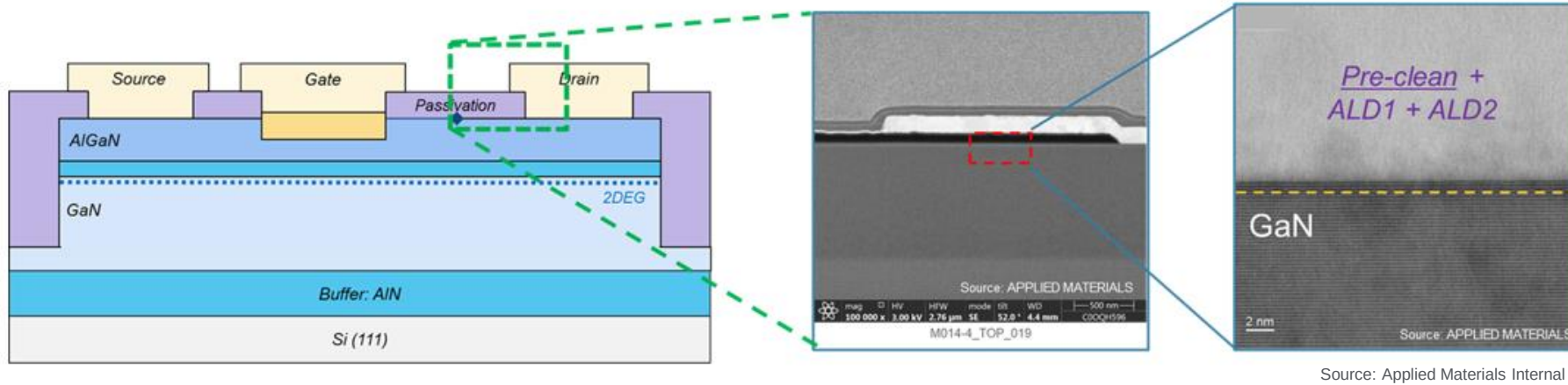
Architecture	Planar	Gate recess	Nano channel	Vertical
	Normally on	Normally off	High density	High voltage
Die surface		↓	↓↓↓	
Efficiency		↑	↑↑↑	↑↑↑↑

p-GaN Schottky gate HEMTs

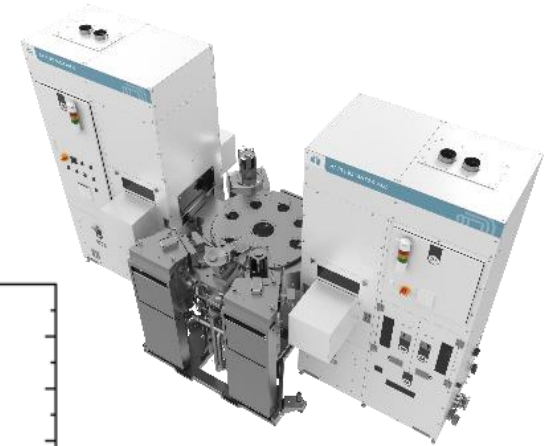
- ALD dielectric layer deposition can be combined with in-situ clean
 - Remote plasma in-situ clean
 - **PEALD AlN** interface layer
 - Thermal **ALD Al₂O₃** capping layer
- **ALD AlN/Al₂O₃** used to passivate AlGaN barrier surface
- ALD layer influences
 - » Dynamic $R_{DS(on)}$ dispersion
 - » 2DEG
 - » Sub-threshold characteristics
 - » Off-state performance
- ALD metal layer (i.e. **ALD TiN**) can also be applied as Schottky gate metal on p-GaN.

ALD can enable future architectural changes

GaN: Selected Applied™ Morpher™ Achievements

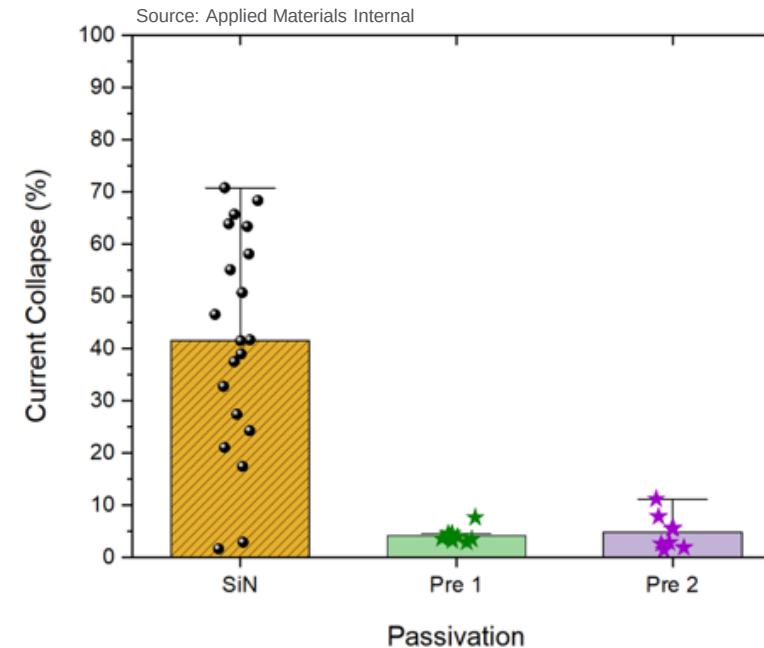


Applied™ Morpher™
Batch ALD + Plasma Enhanced ALD



- GaN HEMT are susceptible to current collapse due to defects at the passivation/GaN interface

IMS tool enables >2x improvement on leakage
>60% improvement in 2DEG density



GaN: Selected Applied™ Morpher™ Achievements

Thermal ALD, no pre-treatment

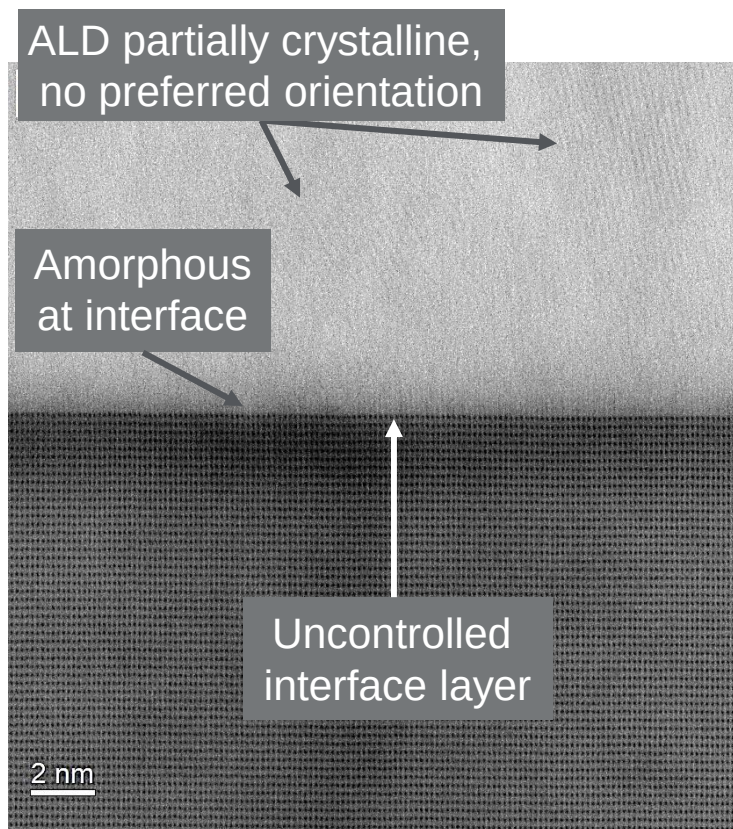
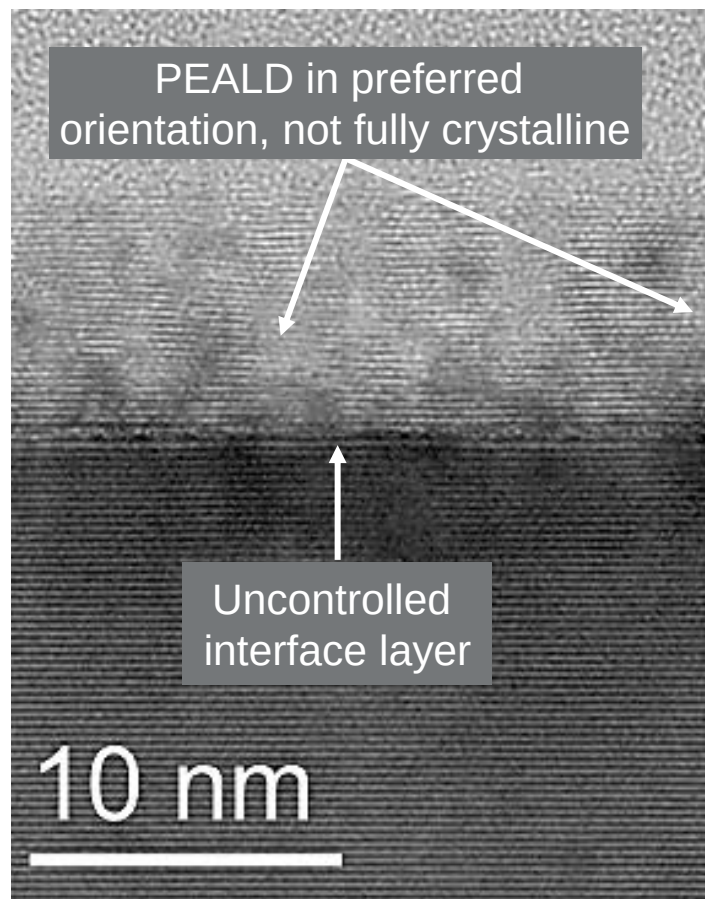
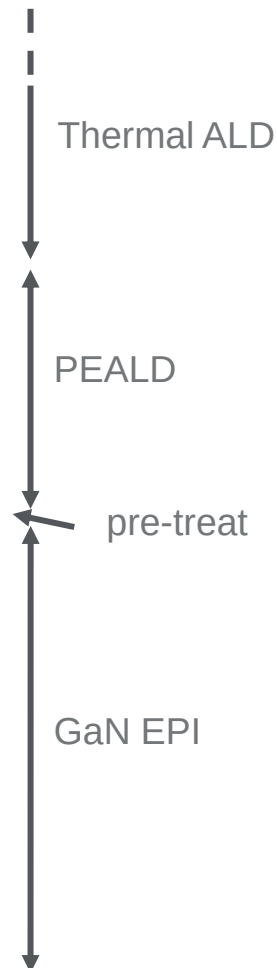
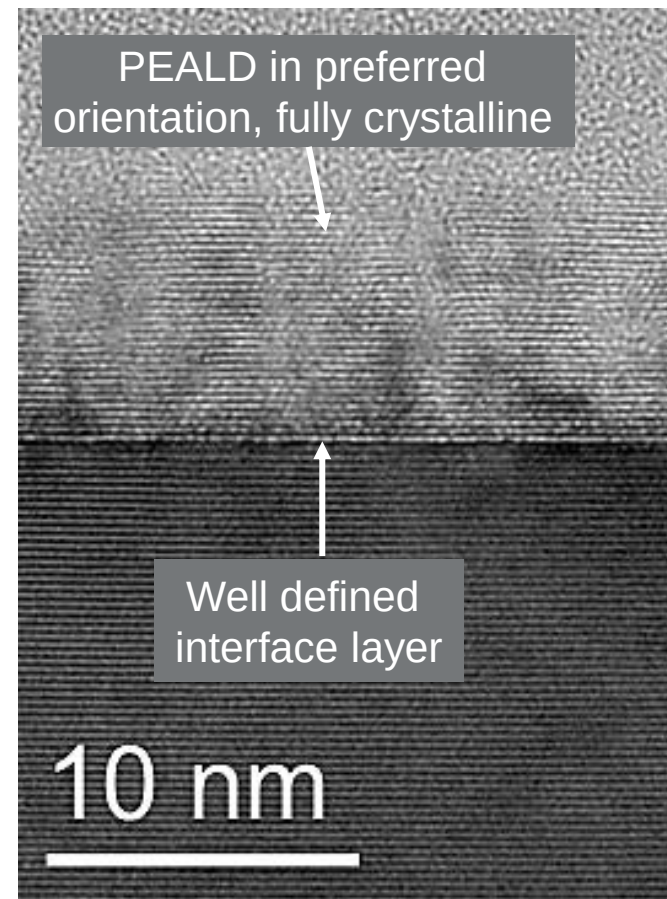


Image sources: Applied Materials Internal

PEALD, no pre-treatment



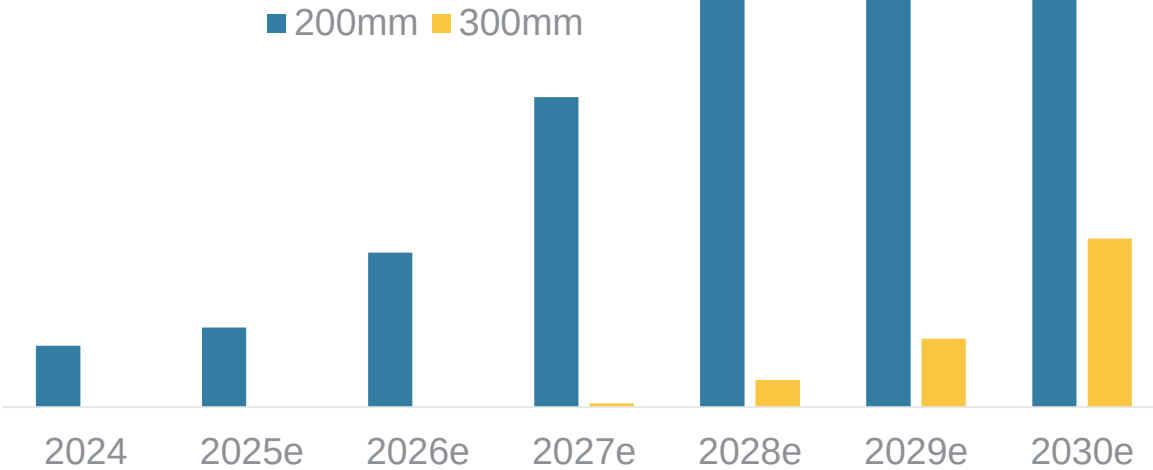
PEALD w/ pre-treatment



In-situ pretreatment for
interface control & EPI-like crystallinity of PEALD

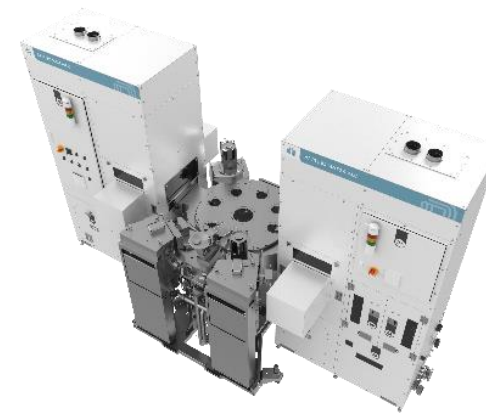
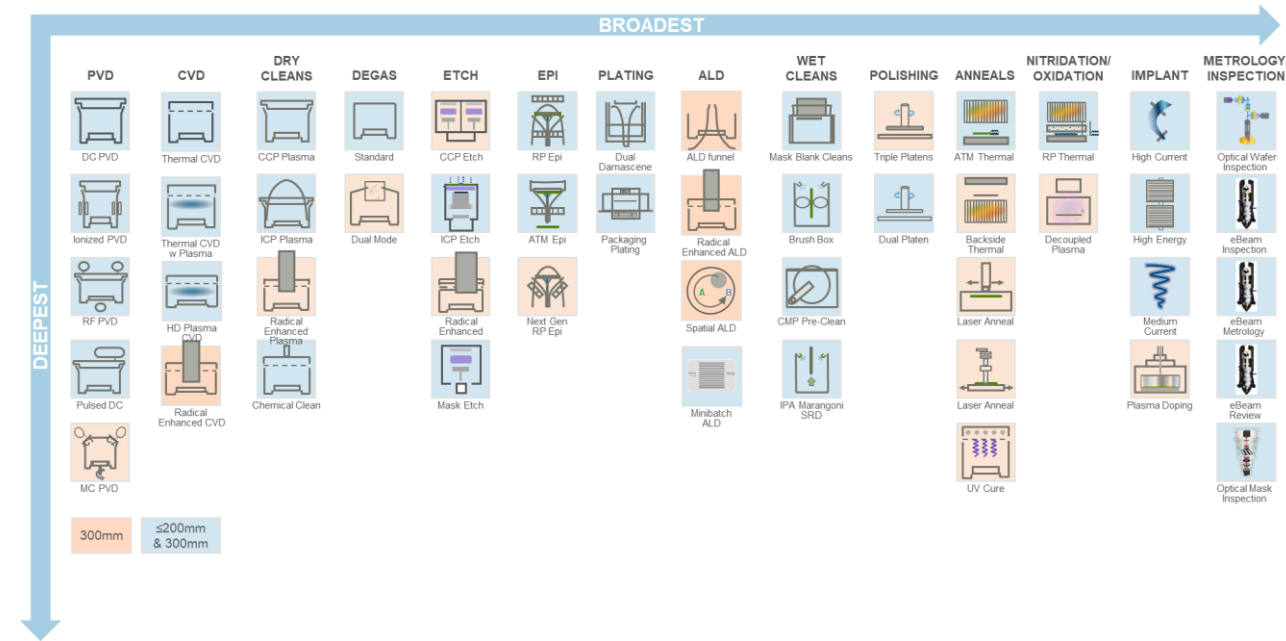
Outlook: Roadmap GaN

Wafer size market evolution (in total surface area)



Source: Applied Materials Internal

- ALD enables inflections in GaN
 - » Significant efficiency gains
 - » Soft pre-treatment and deposition for interface control
 - » Conformality needed for new architectures
- ALD readily available for 200 and 300 mm
 - » Mini-batch ALD solution – 25 wafers 200 mm Morpher™
 - » Mini-batch ALD solution – 15 wafers 300 mm Sprinter™



Applied™ Morpher™ Batch ALD cluster 200 mm



Applied™ Picosun™ Sprinter™ Batch ALD cluster 300 mm

Thank you very much for your attention!

