Massachusetts Institute of Technology

REMOTE EPITAXY and SELECTIVE EPITAXY on vdW materials for layer transfer

July 8, 2022

- This material is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Solar Energy Technologies Office Award Number DE-EE0008558.
- The views expressed herein do not necessarily represent the views of the U.S.Department of Energy or the United States Government.

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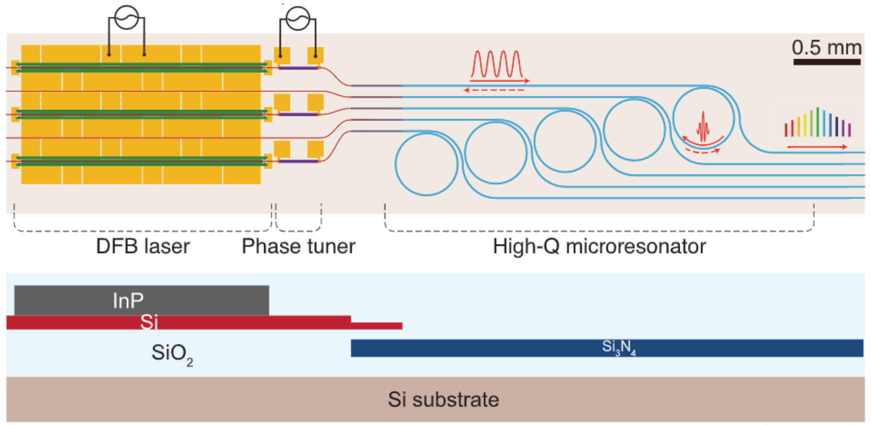
Heterointegrated III-V & III-N membranes

Photonics applications

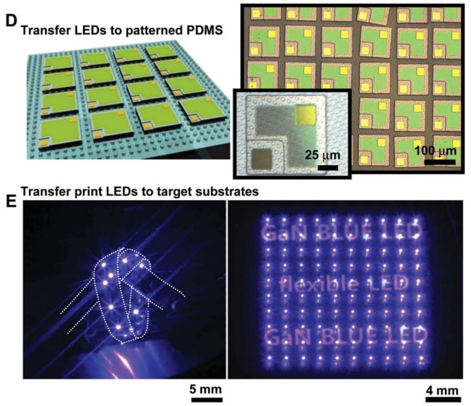
Integrated Si photonic platform



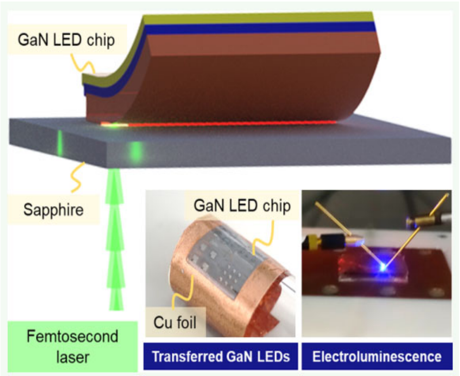
Science, 373, 99-103 (2021)

Displays (microLED, AR, VR)

GaN-based flexible microLEDs



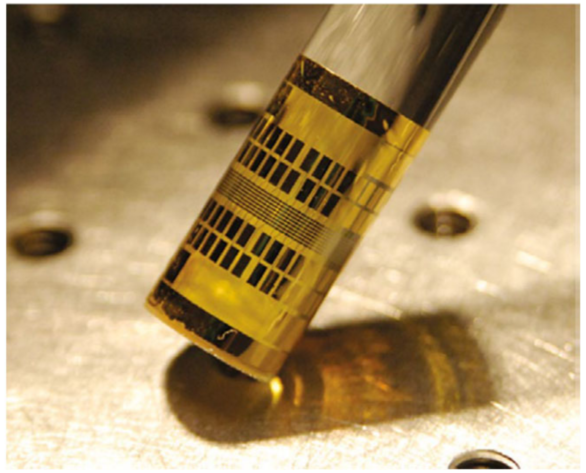
Small 8, 1641 (2012)



ACS App. Elect. Mat. 3, 778 (2021)

Infrared imaging

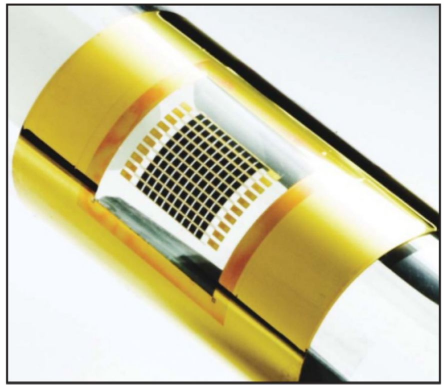
Wide field-of-view (FOV) InGaAs FPA



ACS Photon. 3, 670–676 (2016)

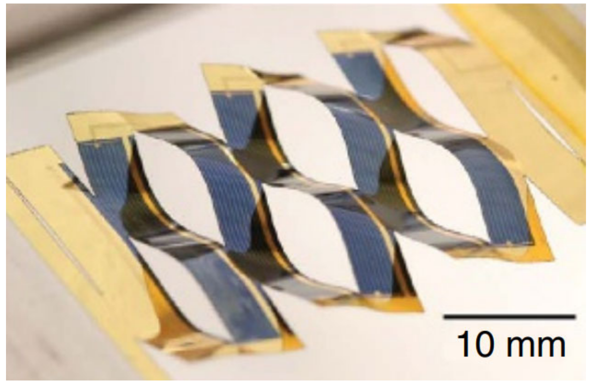
High-efficiency solar cells

Curved/flexible GaAs solar cell



Nature, 465, 329-334 (2010)

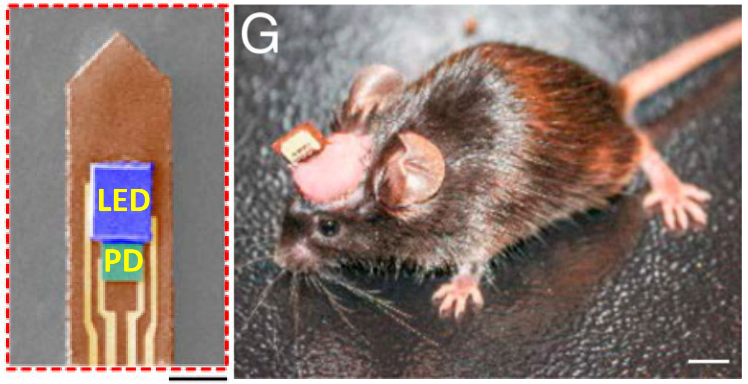
Kirigami GaAs solar cell for integrated solar tracking



Nat. Commun. 6, 8092 (2015)

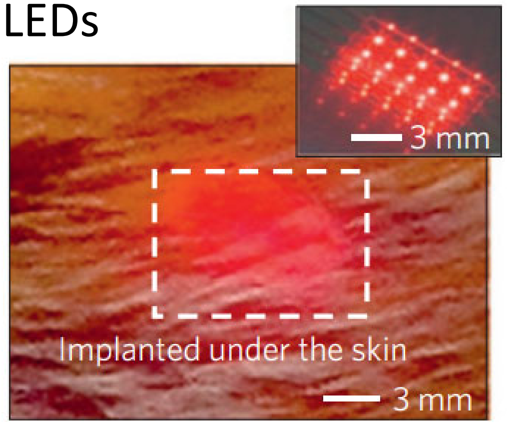
Bioapplications

Neural probe / optogenetics



PNAS, E1374-E1383 (2018)

Stretchable & implantable LEDs



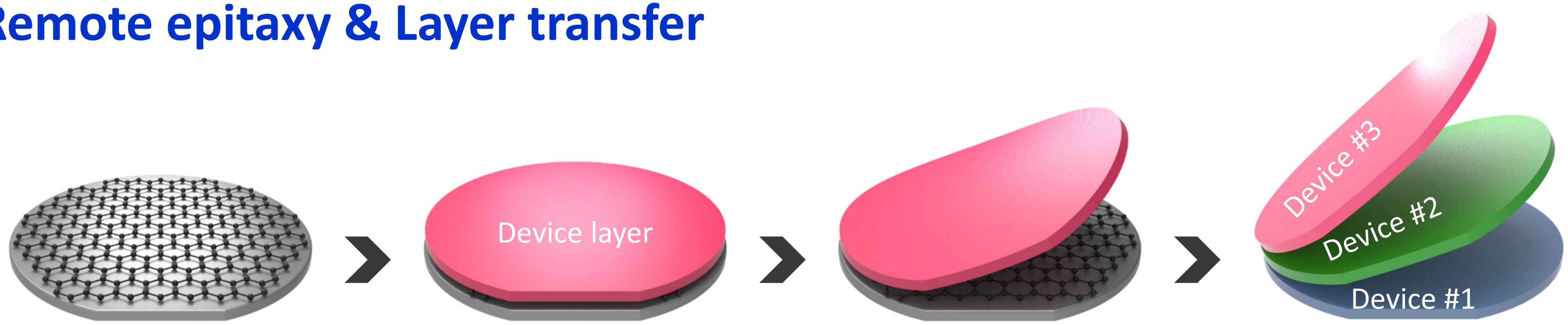
Nat. Mat., 9, 929–937 (2010)

Current layer transfer technology (ELO/LLO/spalling/bonding+wafer etching/smartcut)

: Limits in *throughput, interface roughness, cost, universality*

Remote epitaxy & 2DLT for membrane production

Remote epitaxy & Layer transfer



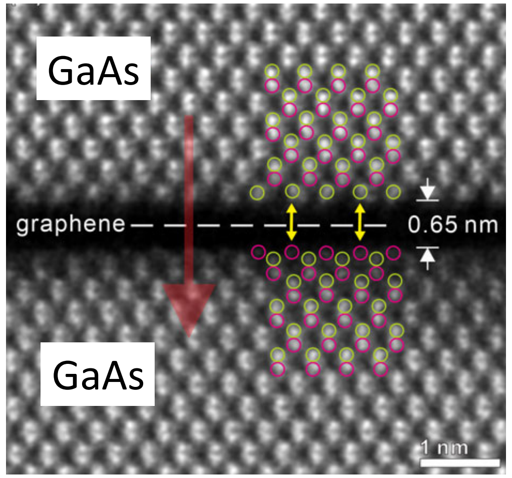
Graphene on wafer | Epitaxial growth | Release | Stack

Nature, 544, 340 (2017)

Graphene transparency enables epitaxy through graphene

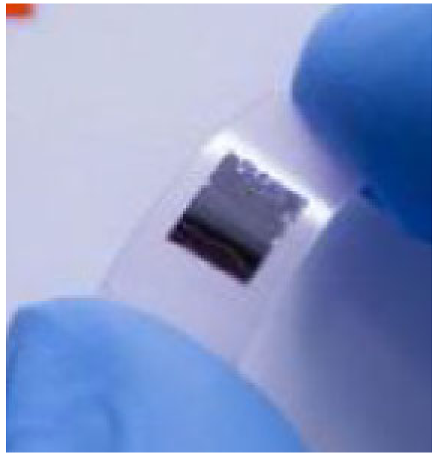
Graphene

x-STEM

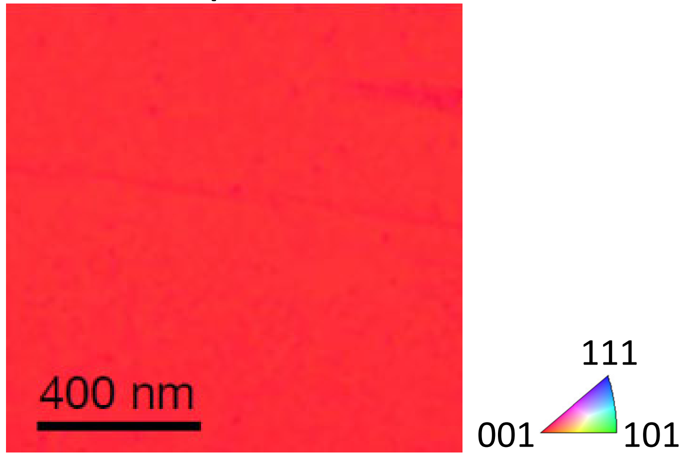


Weak vdW interface enables membrane exfoliation

Exfoliated GaAs

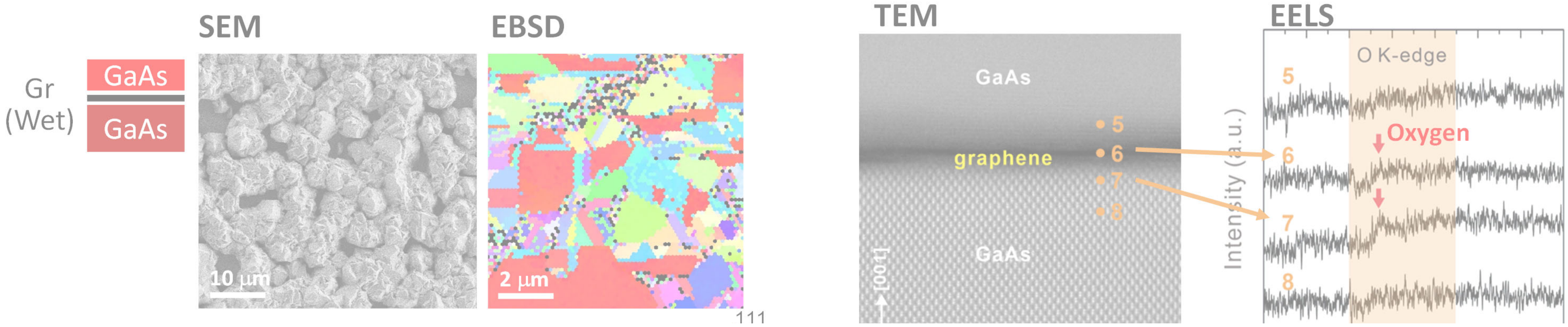


EBSD map

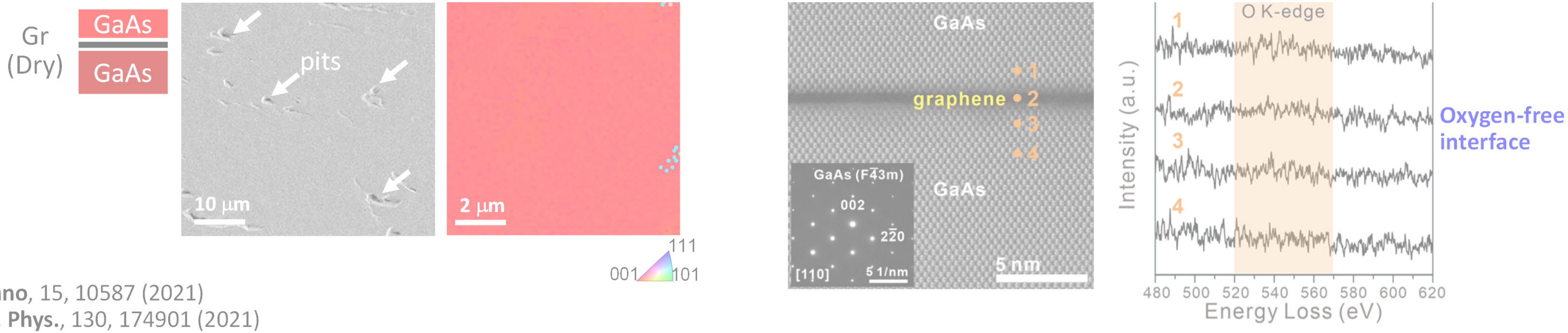


Challenges in Remote epitaxy: Interface control

Interfacial oxide formed during **Wet transfer** → **Failure of remote epitaxy**



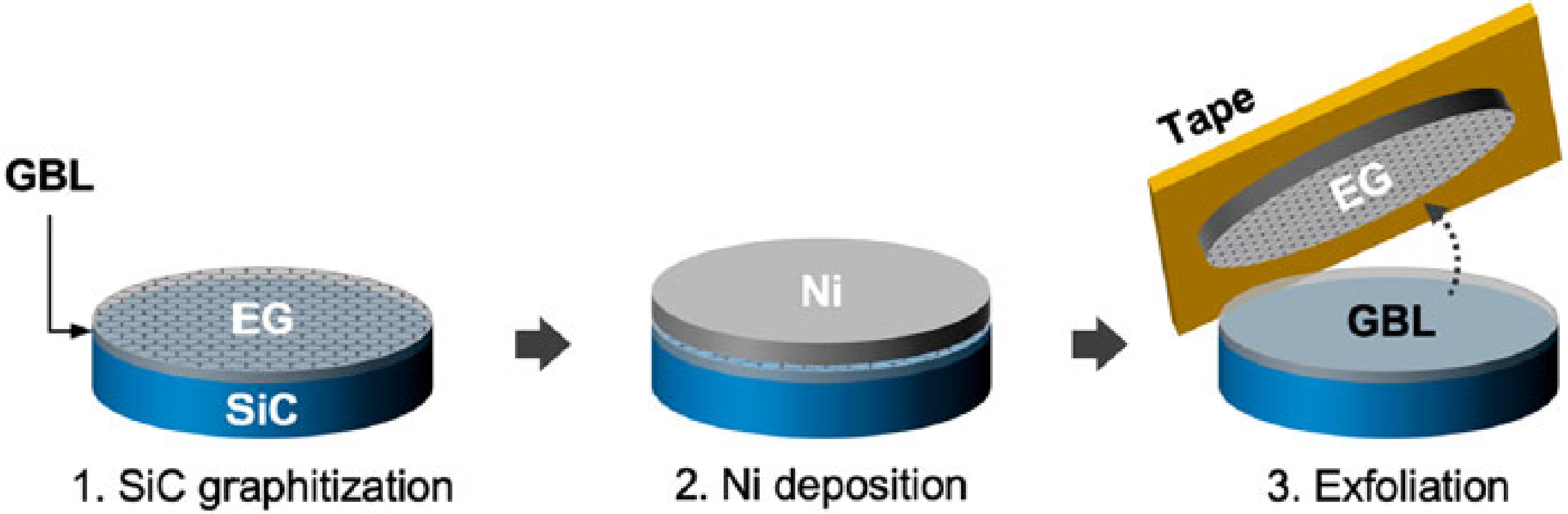
***Transfer-free 2D materials* is essential for advancing remote epitaxy**



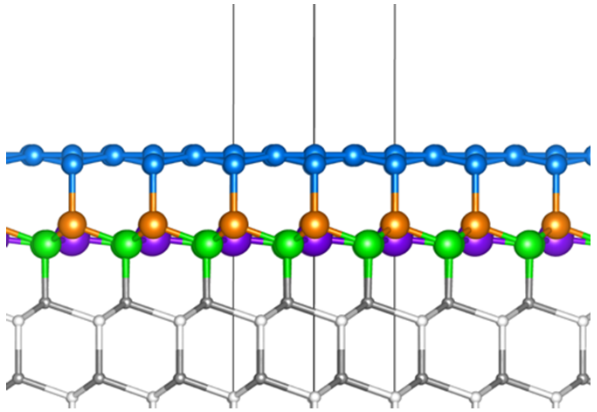
ACS Nano, 15, 10587 (2021)
J. Appl. Phys., 130, 174901 (2021)

Graphitized SiC as growth template

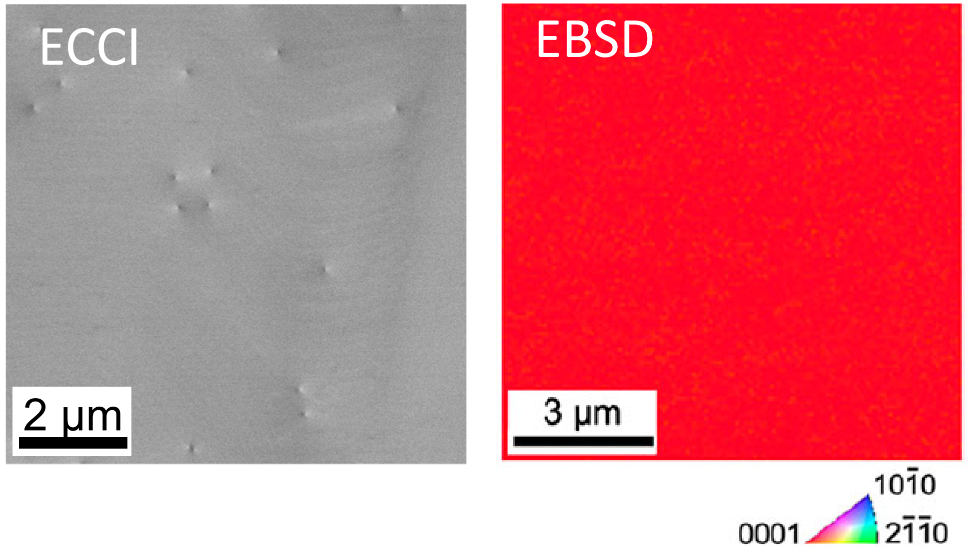
Graphene buffer layer (GBL) on SiC for remote epitaxy template



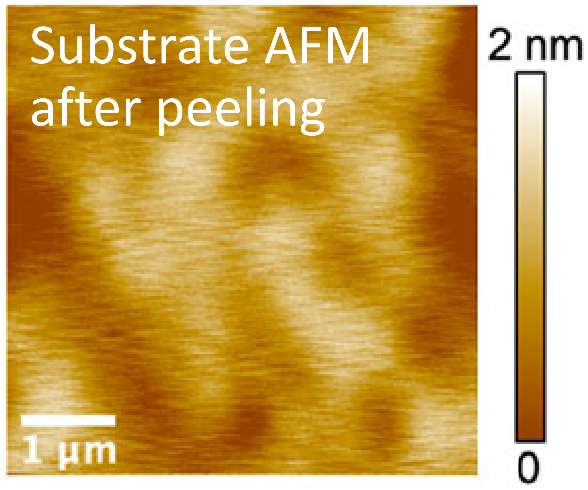
GBL structure

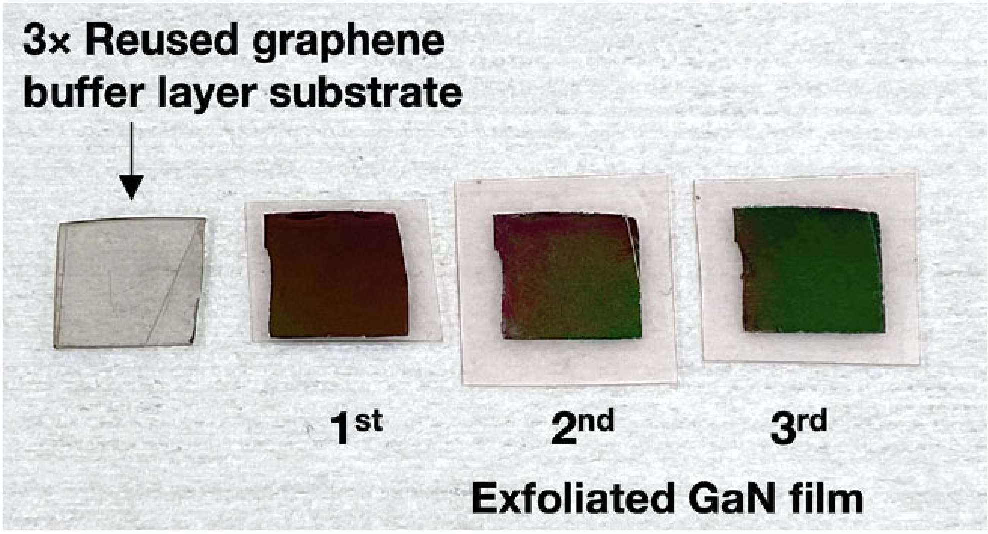


High-quality GaN growth on GBL



Pristine substrate after exfoliation
→ Substrate can be reused



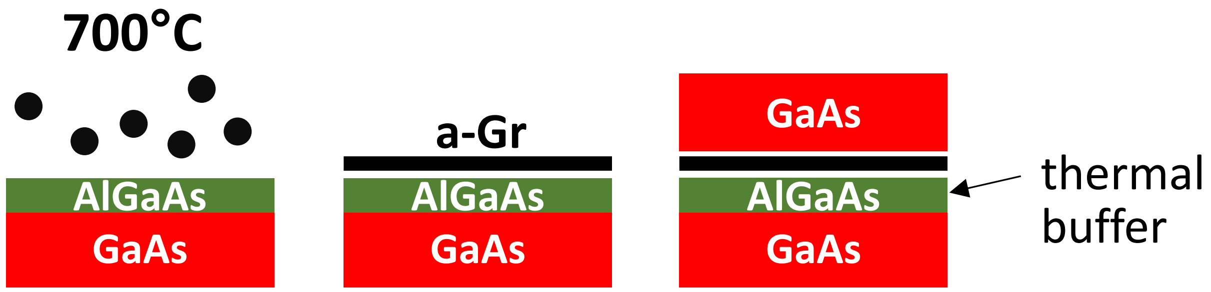


Nano Lett. 21, 4013 (2021)

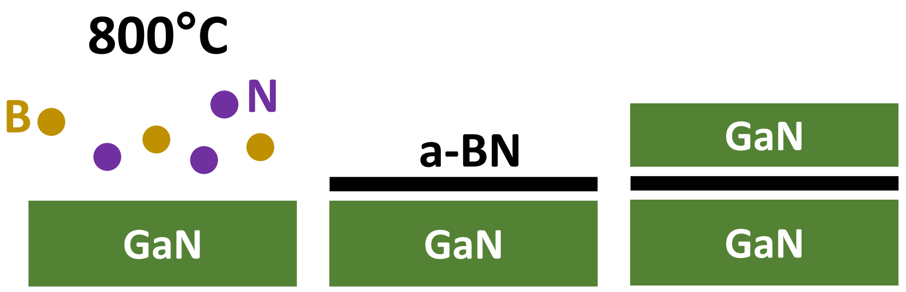
“GROWN” 2D materials for remote epitaxy

Low-temperature grown 2D materials are “amorphous sp² materials”

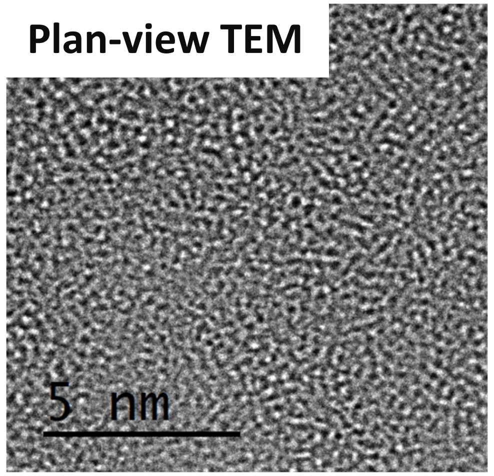
Single-run MOCVD process

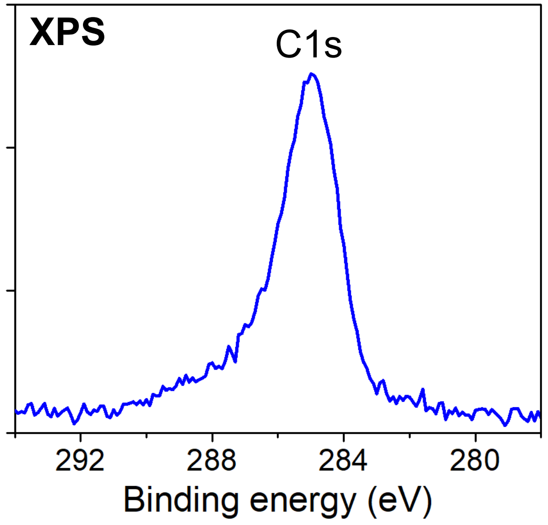


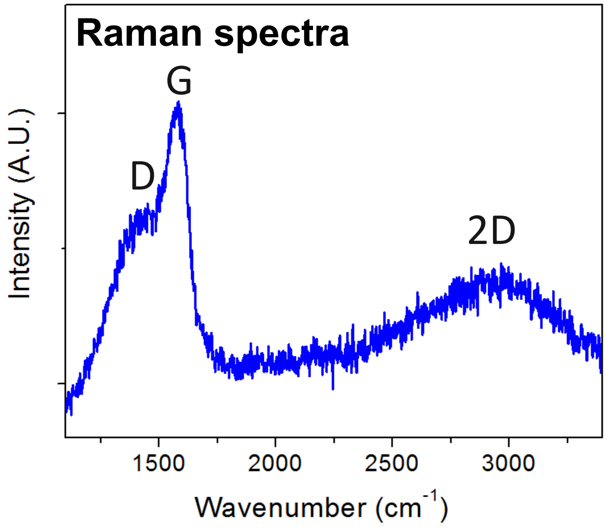
Single-run MBE process



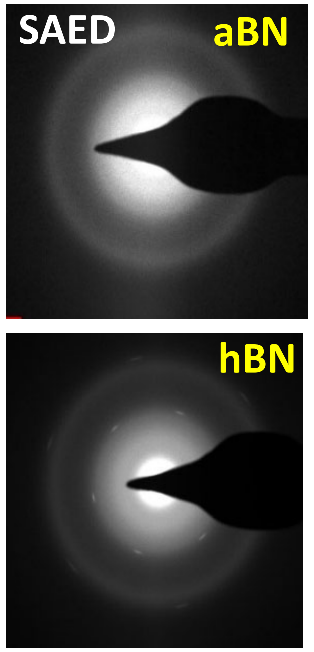
amorphous graphene (a-Gr) on AlGaAs grown at 700°C

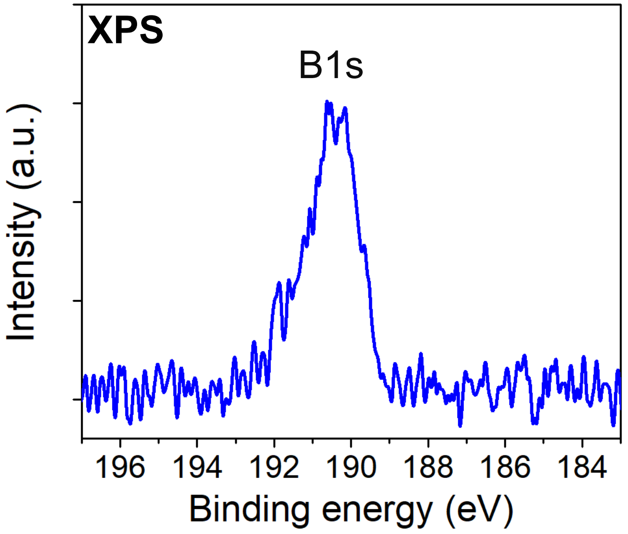






amorphous boron nitride (a-BN) on GaN grown at 800°C

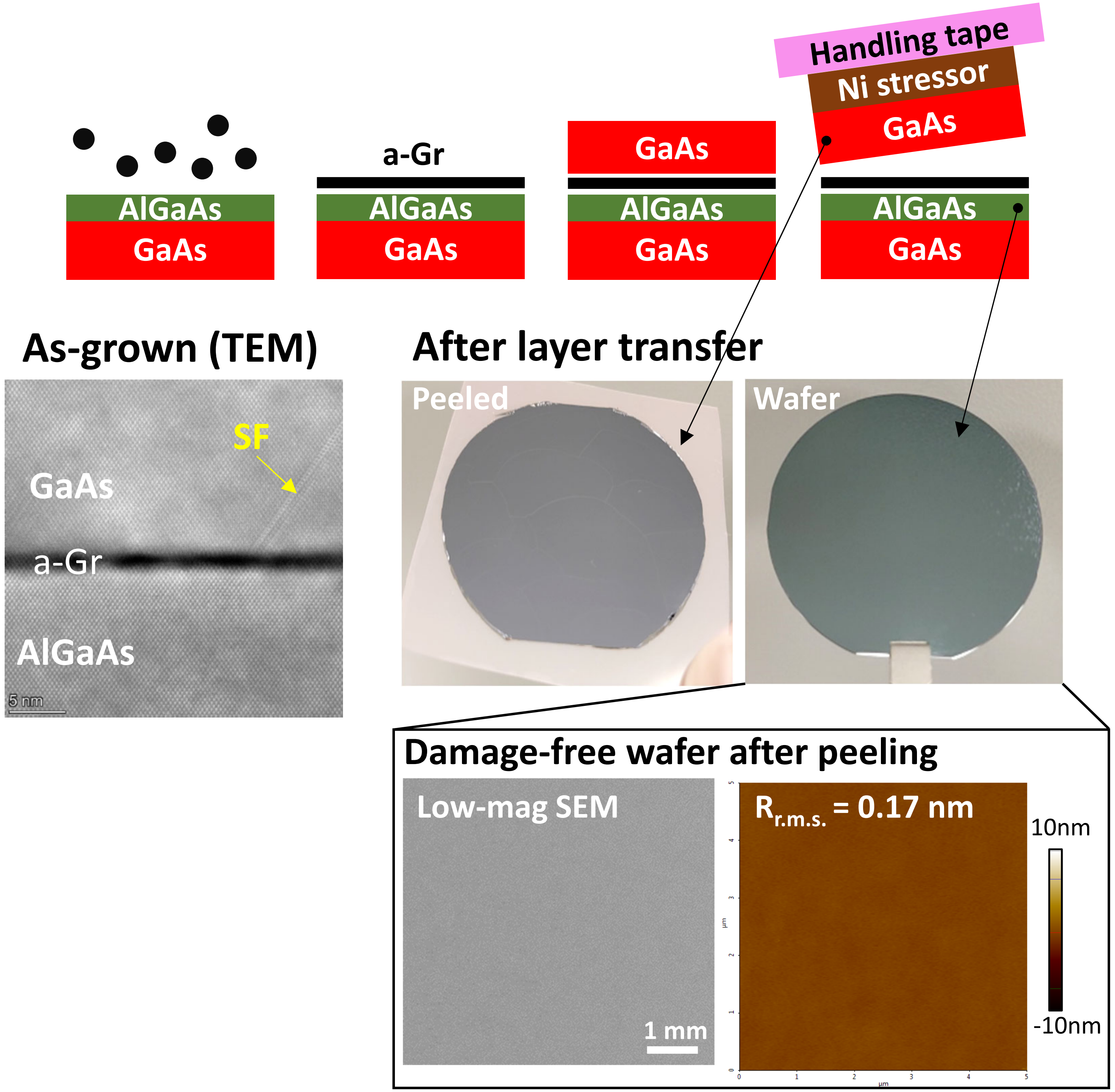




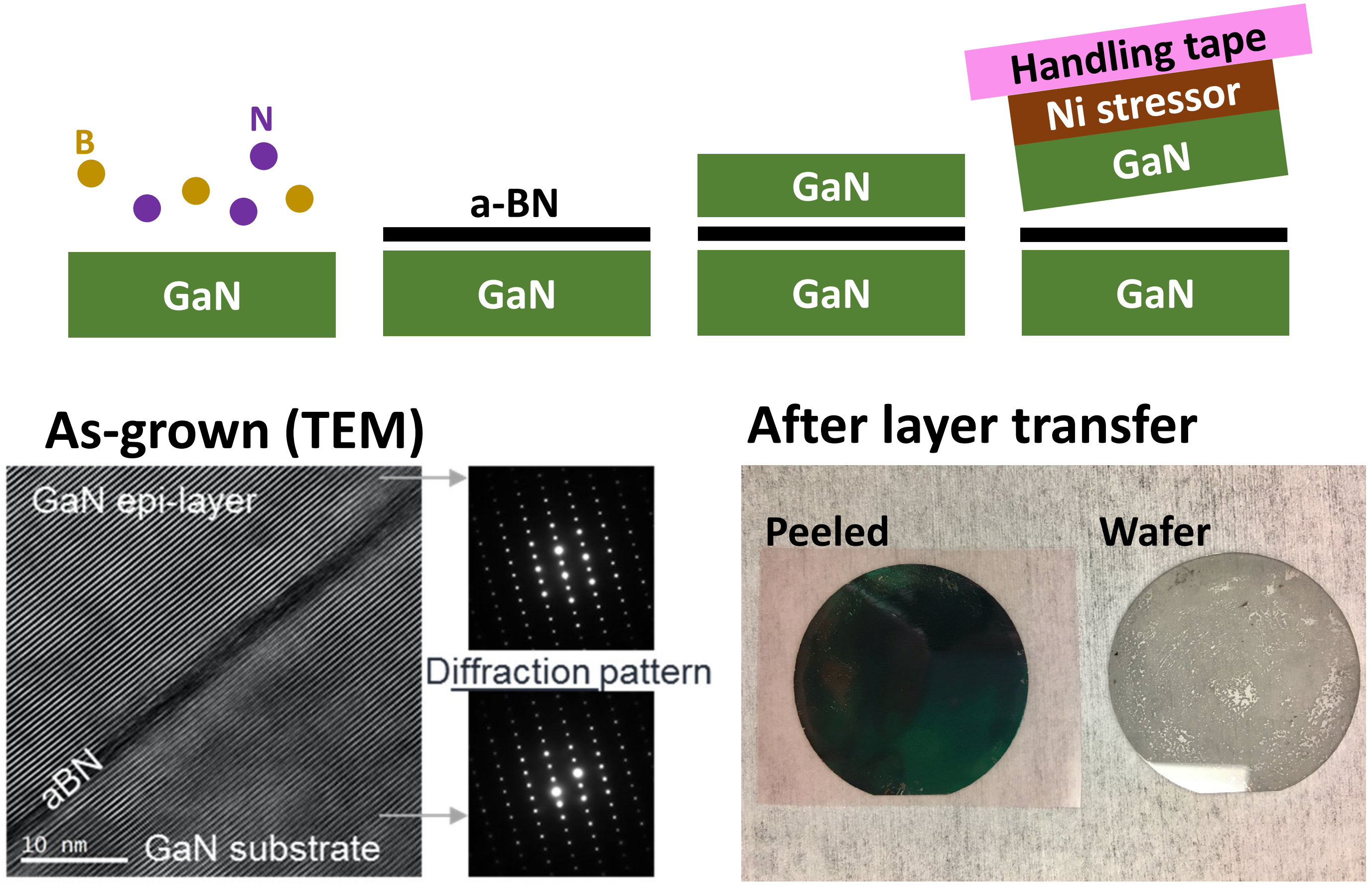
arXiv.2204.08002

Wafer-scale remote epitaxy

GaAs remote epitaxy & Layer transfer



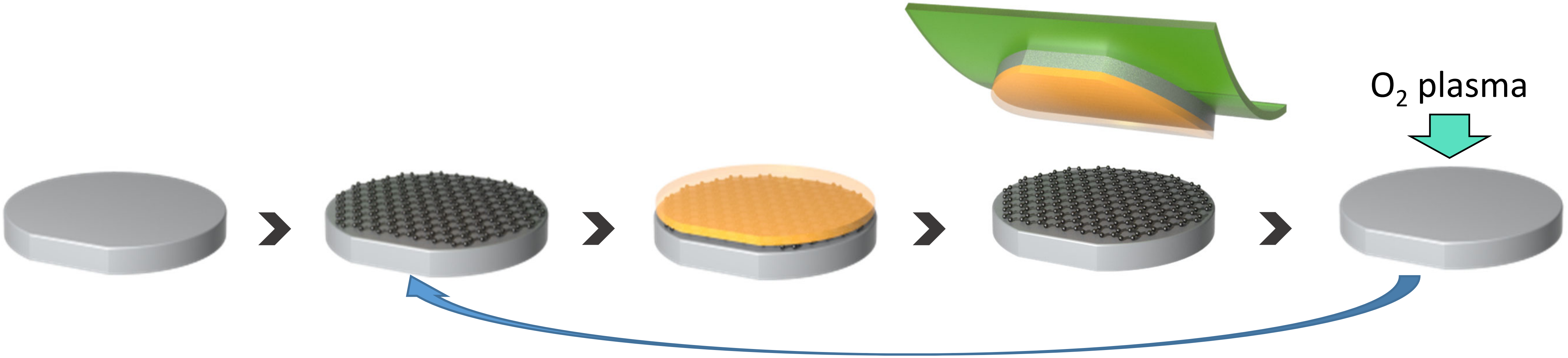
GaN remote epitaxy & Layer transfer

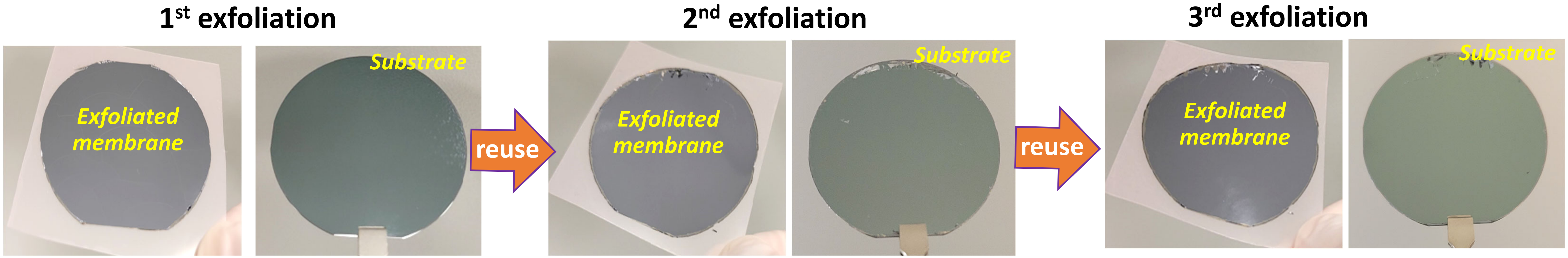


Wafer-scale remote epitaxy of III-V & III-N is demonstrated.

Repeated wafer recycle & membrane production

Wafer recycling process

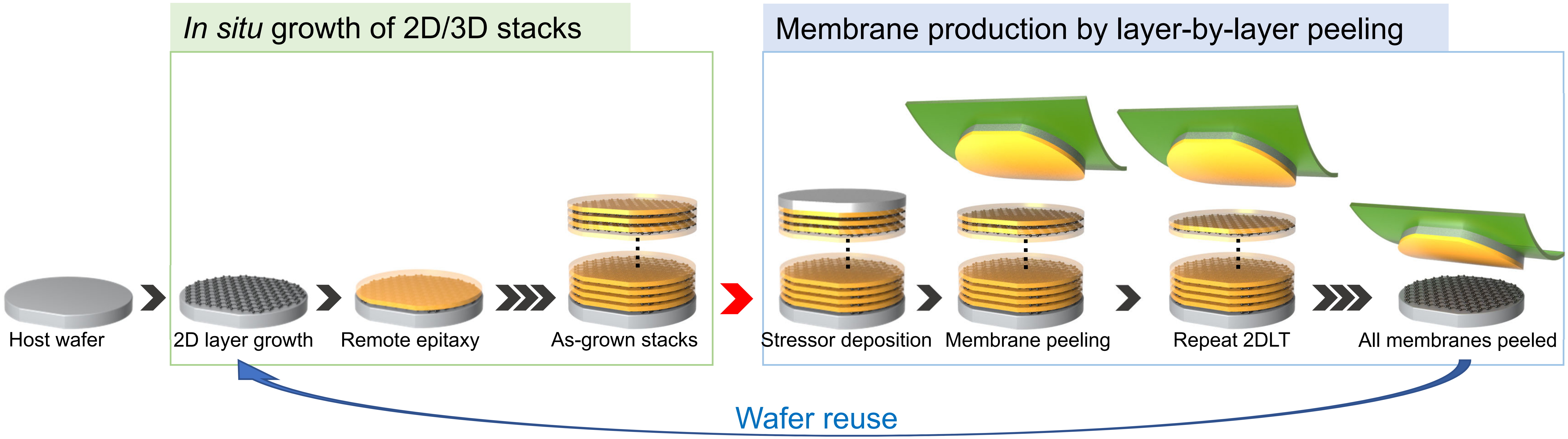




Wafer is recycled to produce multiple GaAs membranes

arXiv.2204.08002

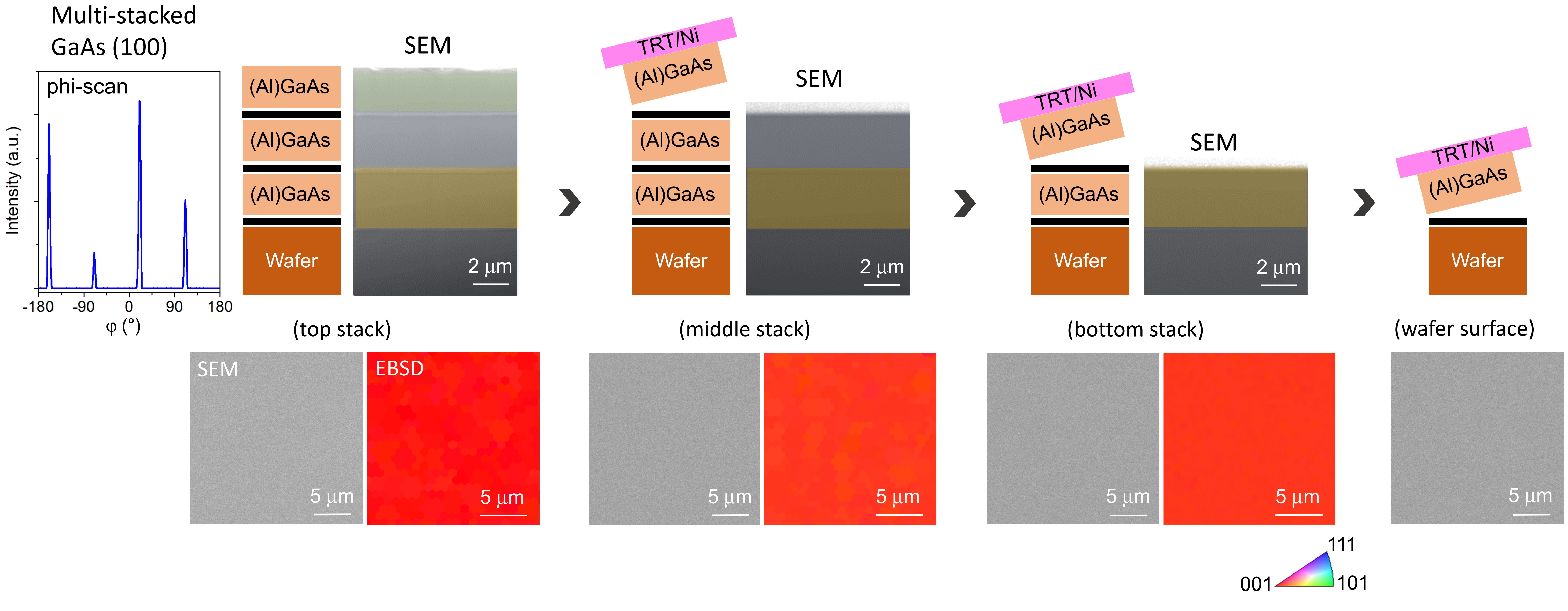
“Multi-stacking” remote epitaxy



Multi-stack growth & Layer-by-layer exfoliation

: Highest throughput enabled by remote epitaxy

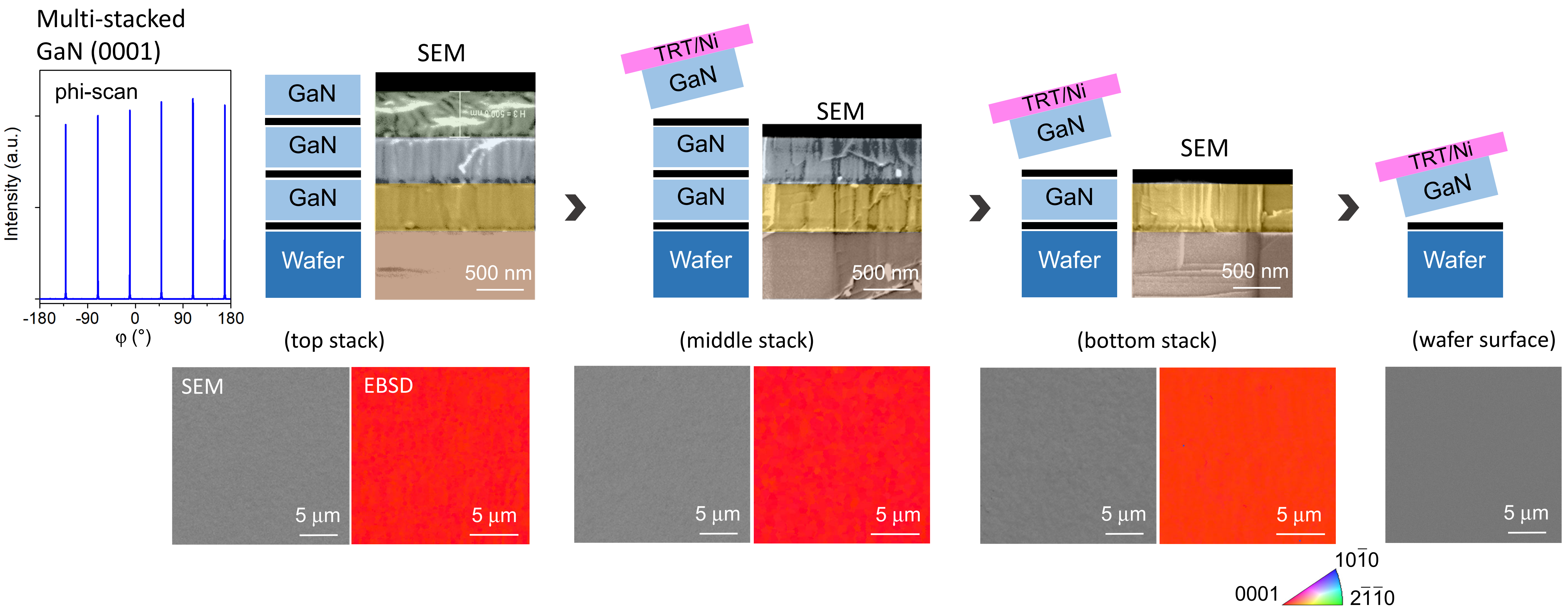
“Multi-stacking” remote epitaxy



Three stacks of III-V/a-Gr grown and exfoliated.

arXiv.2204.08002

“Multi-stacking” remote epitaxy

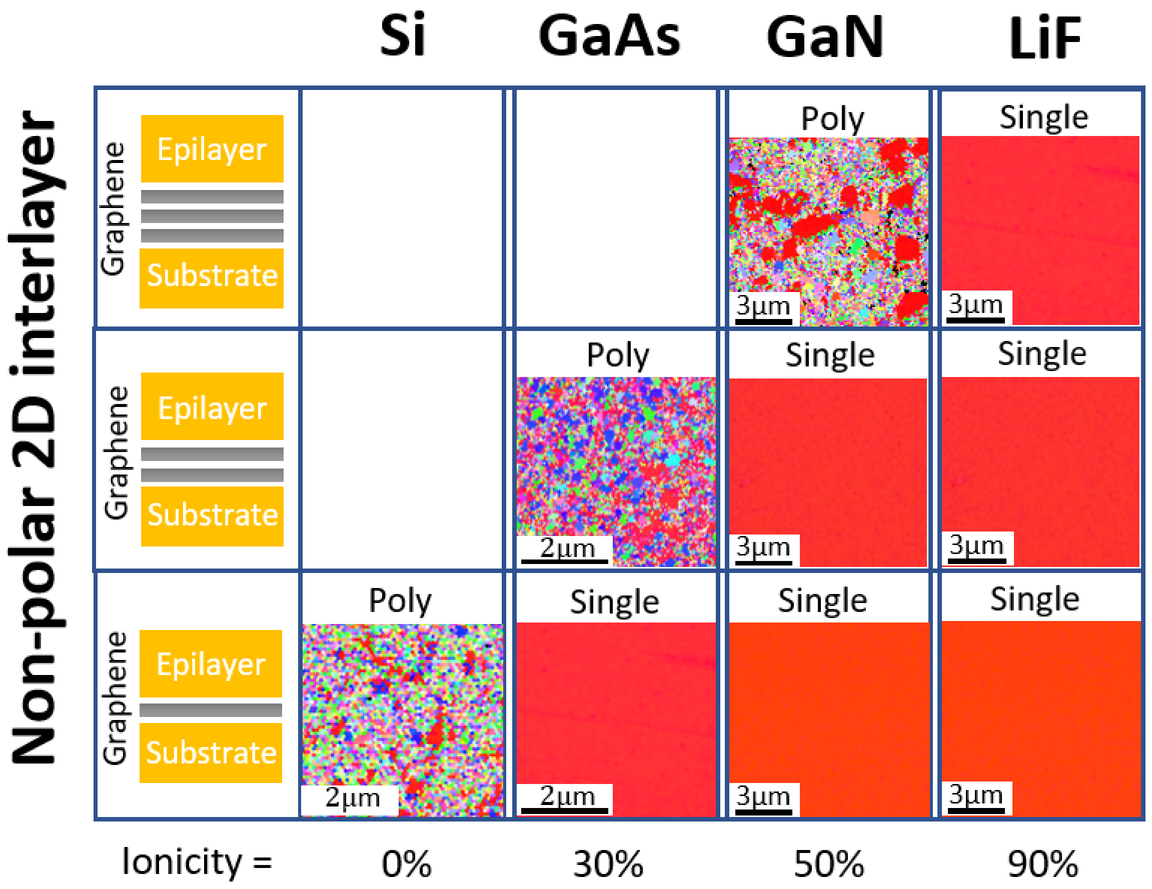


Ultimate wafer-scale single-crystal membrane production technology

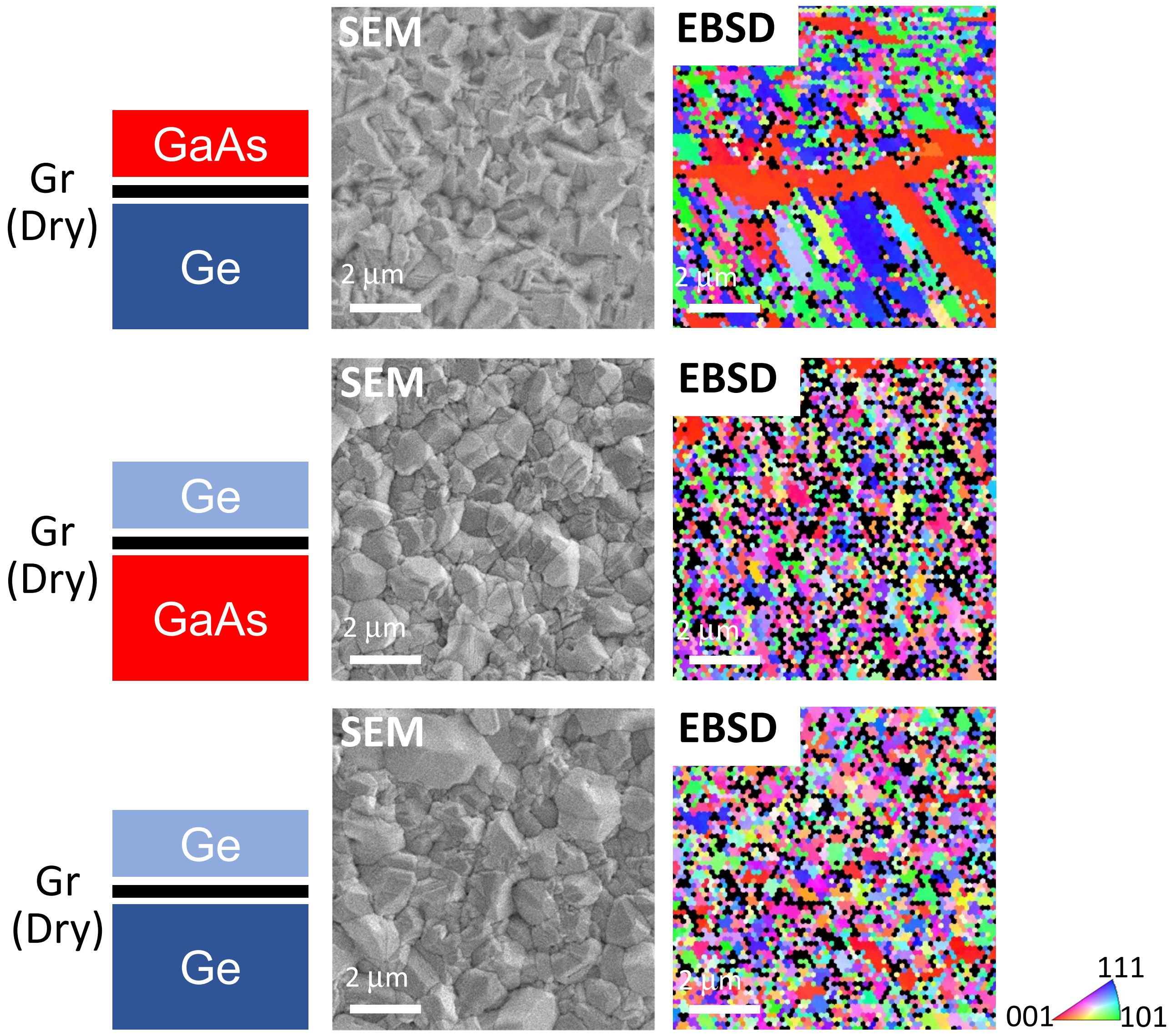
arXiv.2204.08002

Limitation of Remote epitaxy

Ionicity of material governs surface electronic potential



Polycrystal growth from Non-ionic material

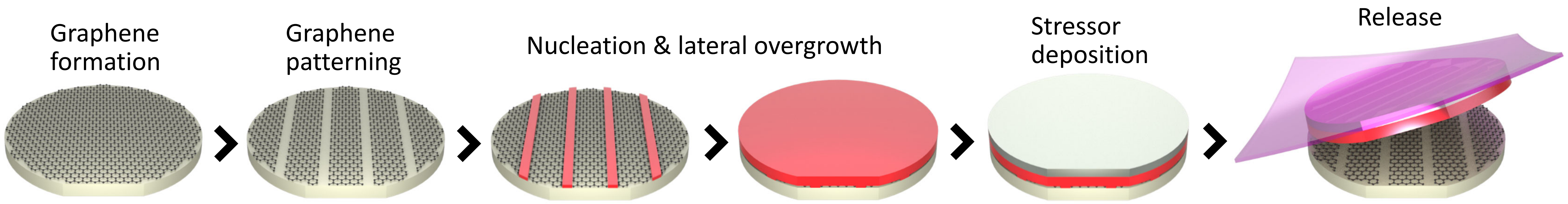


Ionicity (polarity) governs field penetration through graphene.

Elemental materials cannot be utilized as substrates or epilayer.

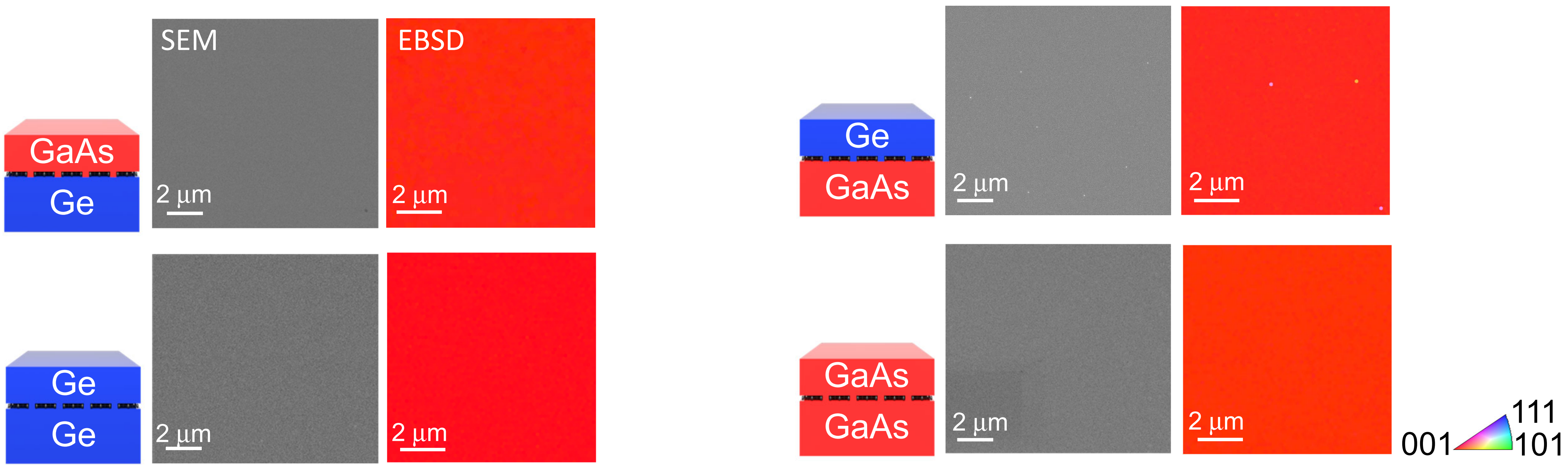
Nature Materials 17, 999 (2018)
ACS Nano, 15, 10587 (2021)

"Nanopatterned graphene" for universal layer transfer

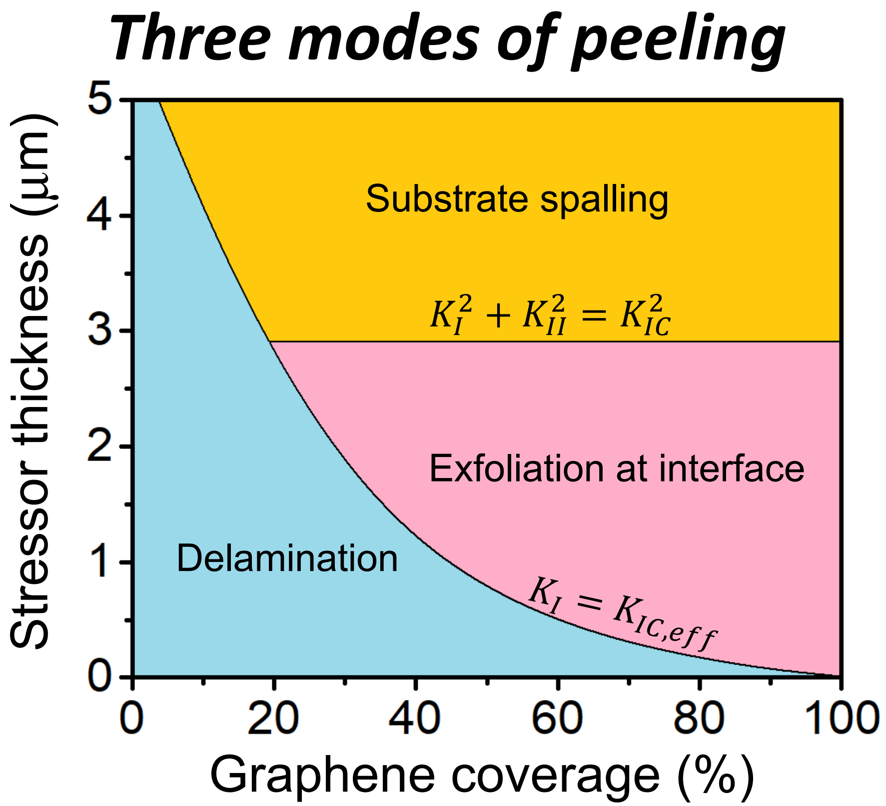


Chemical inertness of graphene enables **selective nucleation**

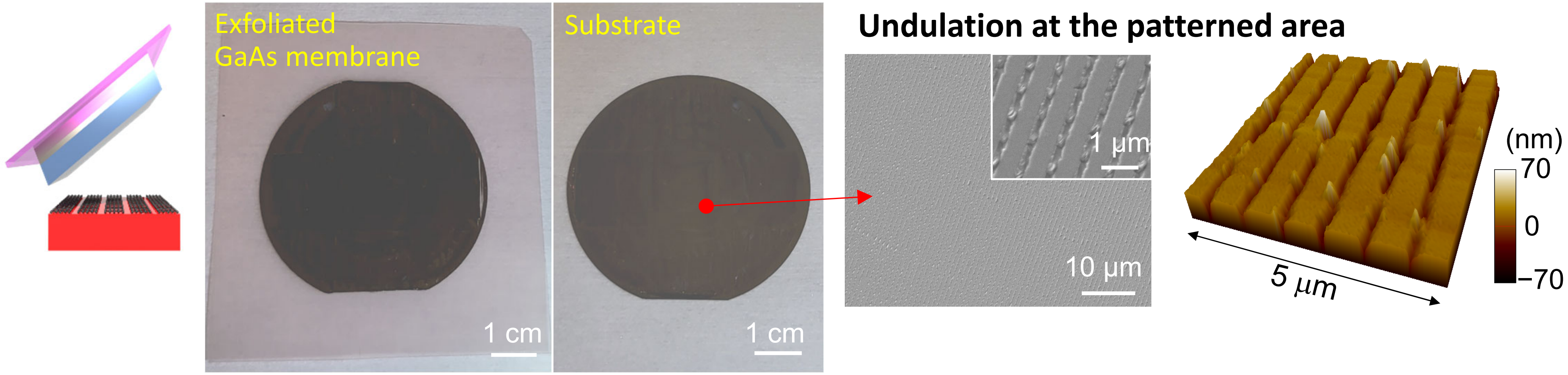
→ **Single-crystal film** involving elemental materials



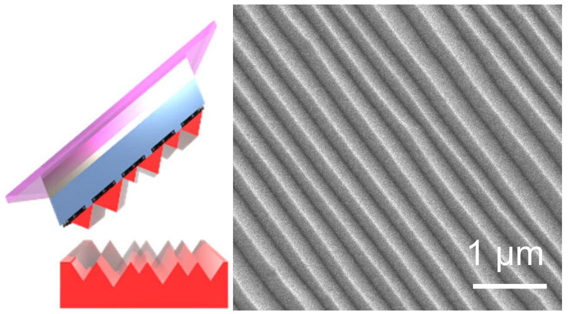
“Nanopatterned graphene” for universal layer transfer



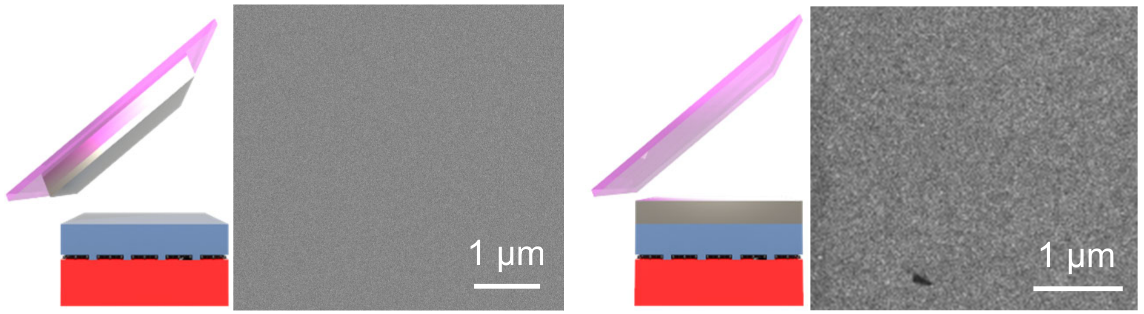
“Wafer-scale exfoliation” at the interface



“Spalling” of wafer



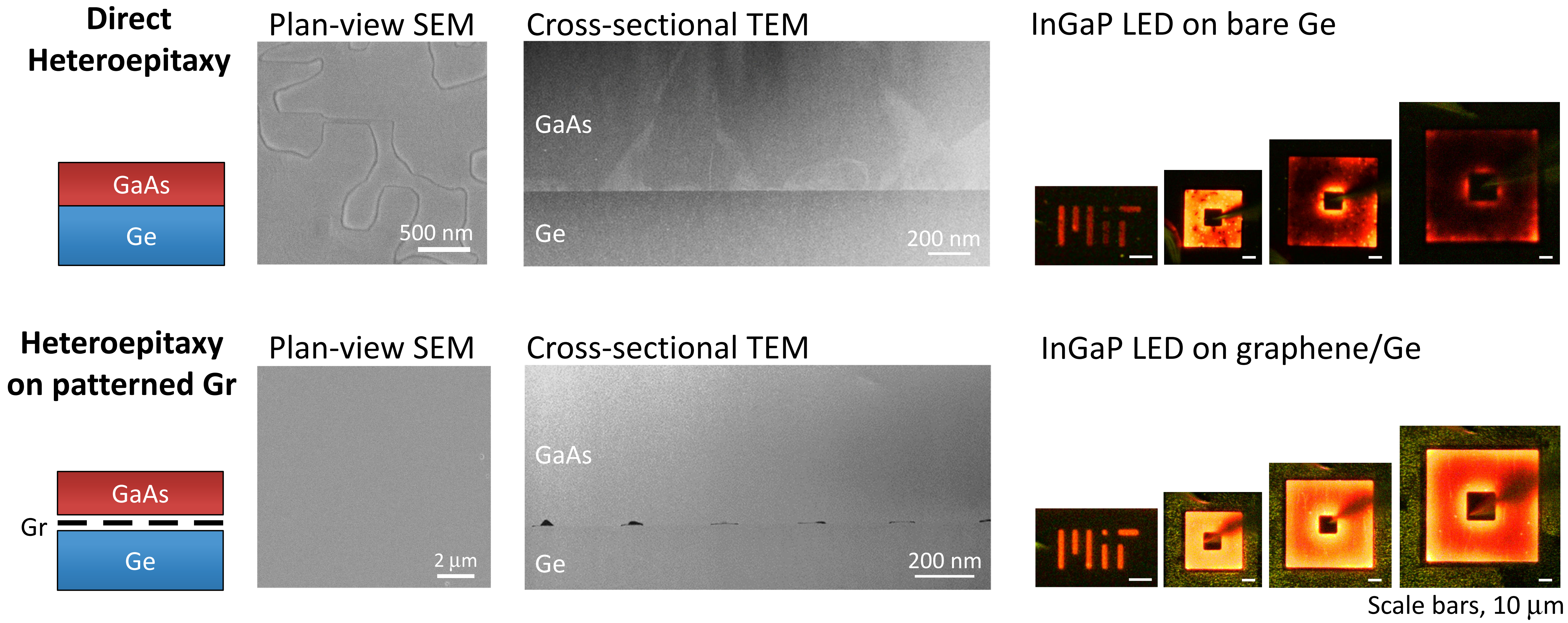
“Delamination” of stressor/tape



Peeling mode can be controlled by Ni stressor condition.

Nat. Nanotech. (under revision)

APB elimination by graphene nanopatterns



- APBs are eliminated by epitaxy through nanopatterned Gr.
- Improved optoelectronic performance by nanopatterned Gr.

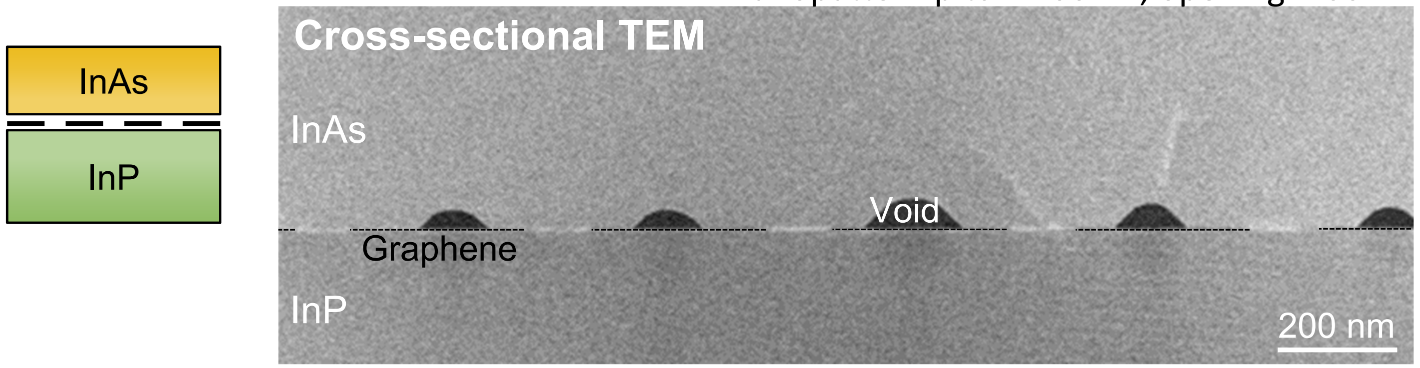
Nat. Nanotech. (under revision)

Dislocation reduction by graphene nanopatterns

In collaboration with Prof. Hwang (OSU)

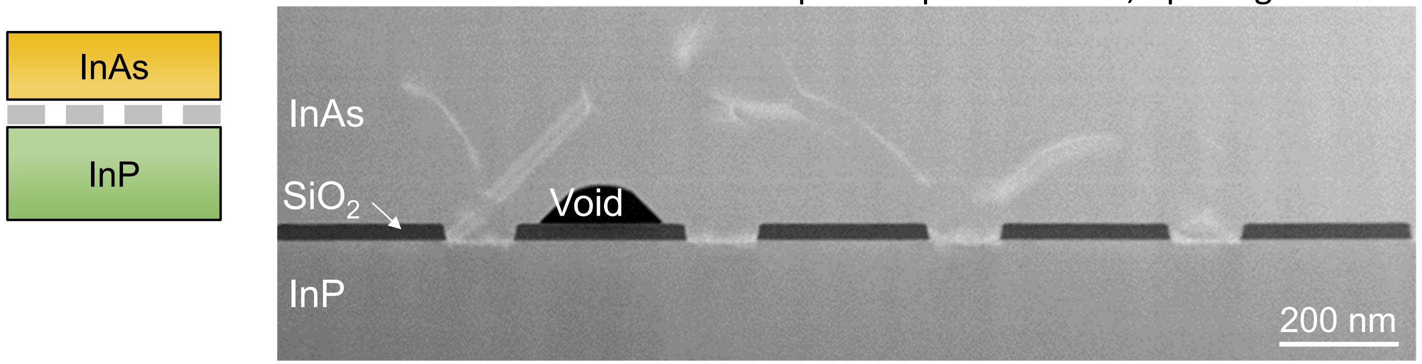
(1) Graphene nanopattern

Nanopattern pitch=400nm, opening=100nm

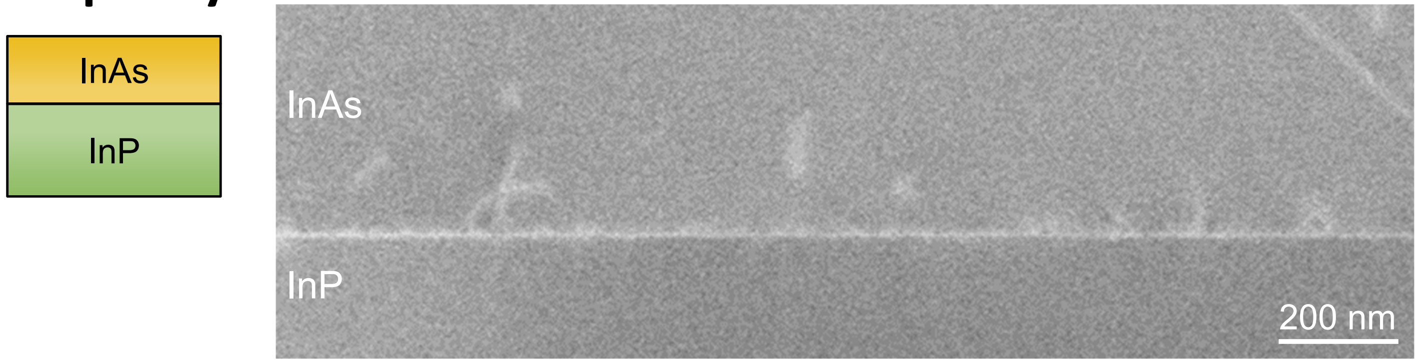


(2) SiO_2 mask (30nm thick)

Nanopattern pitch=400nm, opening=100nm



(3) Direct heteroepitaxy



Lattice-mismatched heteroepitaxy on graphene nanopattern

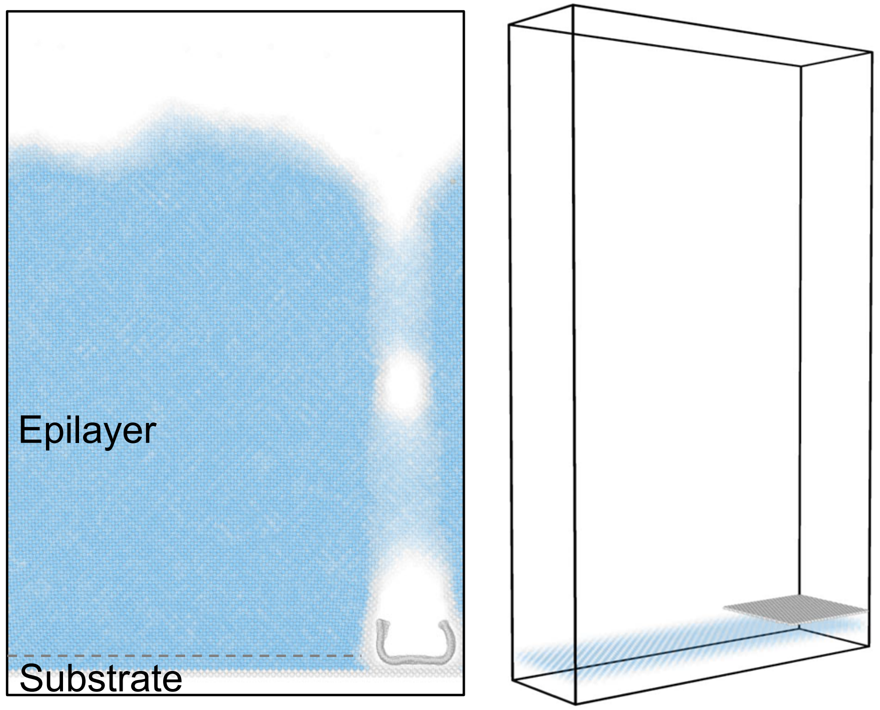
→ Reduced dislocation density

Nat. Nanotech. (under revision)

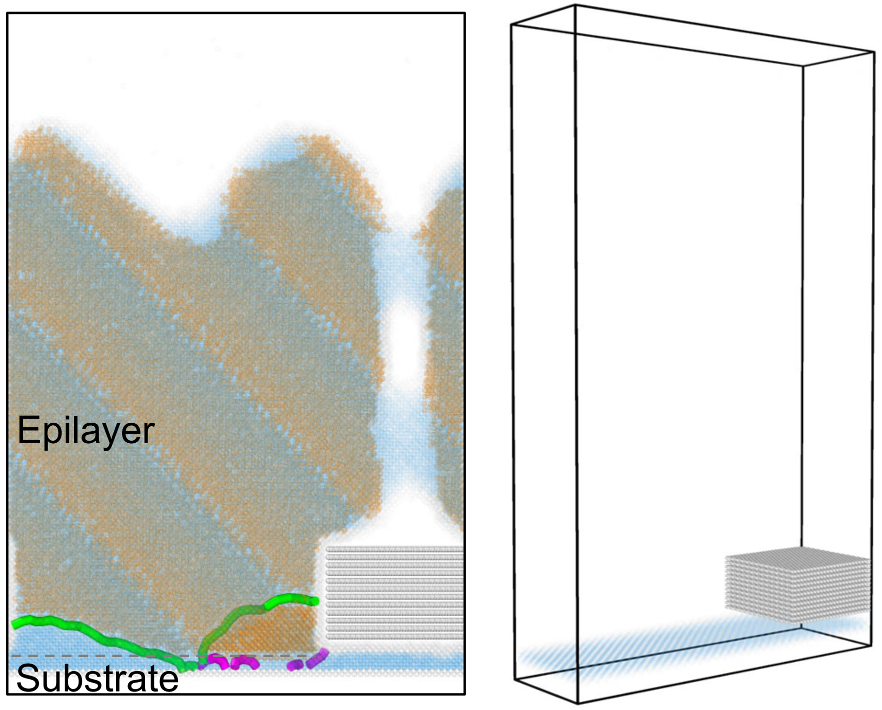
MD simulations to reveal dislocation reduction mechanism

In collaboration with Prof. Shi (RPI)

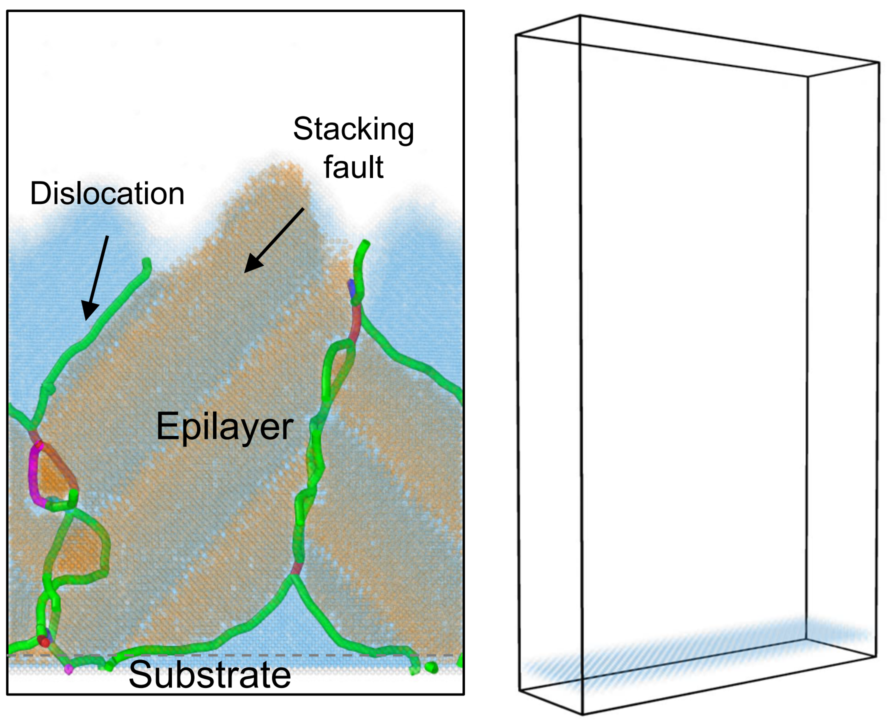
Flexible mask (Graphene)



Thick and rigid mask (SiO_2)



Direct heteroepitaxy (without mask)



*‘**Flexibility**’ of graphene suppresses defect formation*

Opportunities in Heterostructures

Beyond limit of heteroepitaxy

as of 2022

	Diamond (Si, Ge)	Zinc Blend (GaAs, InP, InAs..)	Wurtzite (GaN, AlN..)	Perovskite (STO, BTO..)	Spinel (CFO, MAO..)	Garnet (YIG, GGG..)
Diamond (Si, Ge)		Optical link Focal plane array Transistors	High quality GaN on Si	Ferroelectric 5G, 6G		
Zinc Blend (GaAs, InP, InAs..)	Optical link Focal plane array Transistors		Full color microLEDs Hybrid heterojunction			
Wurtzite (GaN, AlN..)	High quality GaN on Si	Full color microLEDs Hybrid heterojunction			Tunable filter	
Perovskite (STO, BTO..)	Ferroelectric 5G, 6G				ME coupling	
Spinel (CFO, MAO..)			Tunable filter	ME coupling		
Garnet (YIG, GGG..)						

Summary

- "*Grown 2D layer*" enables **wafer-scale, high-throughput membrane production**.
- "*Nanopatterned graphene*" allows for **universal membrane production** and **defect reduction**.

This work is conducted in collaboration with:

- Prof. Yunfeng Shi (RPI)
- Prof. Jinwoo Hwang (OSU)
- Prof. Sungkyu Kim (Sejong Univ.)
- Prof. Sang-Hoon Bae (WashU)
- Prof. Kyusang Lee (UVA)
- Prof. Wei Kong (Westlake Univ.)
- Prof. Geun Young Yeom (SKKU)
- Prof. Suklyun Hong (Sejong Univ.)
- Prof. Jong-Hyun Ahn (Yonsei Univ.)

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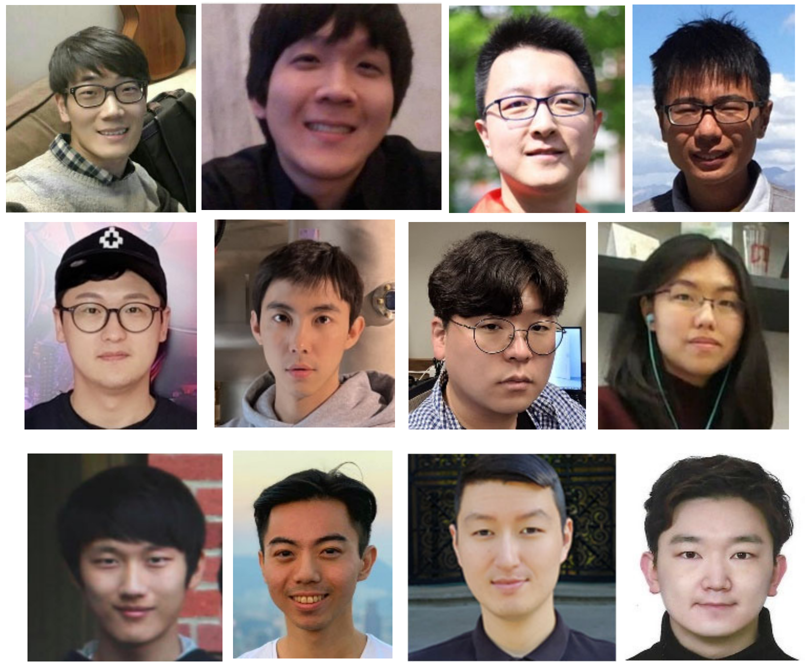
- The views expressed herein do not necessarily represent the views of the U.S.Department of Energy or the United States Government.

Acknowledgement (Prof. Kim group)



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