Massachusetts Institute of Technology

III-V epitaxy for low energy optoelectronics

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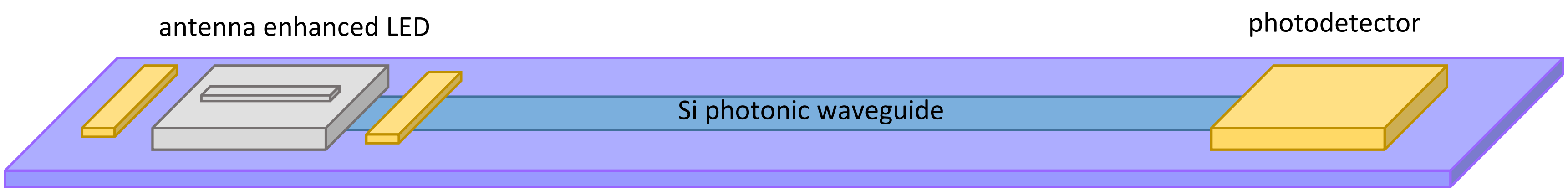
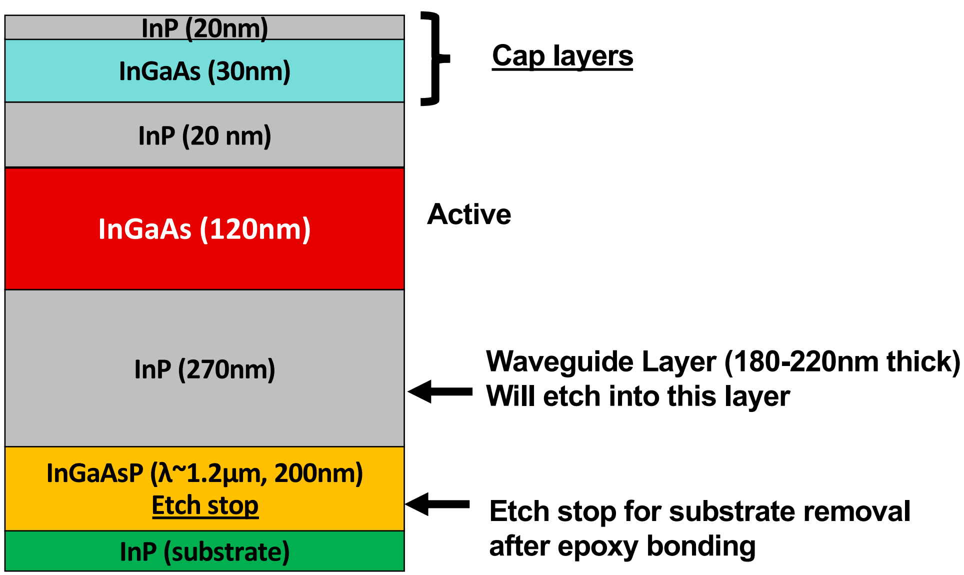
Epitaxial strategies enabling low energy optoelectronics



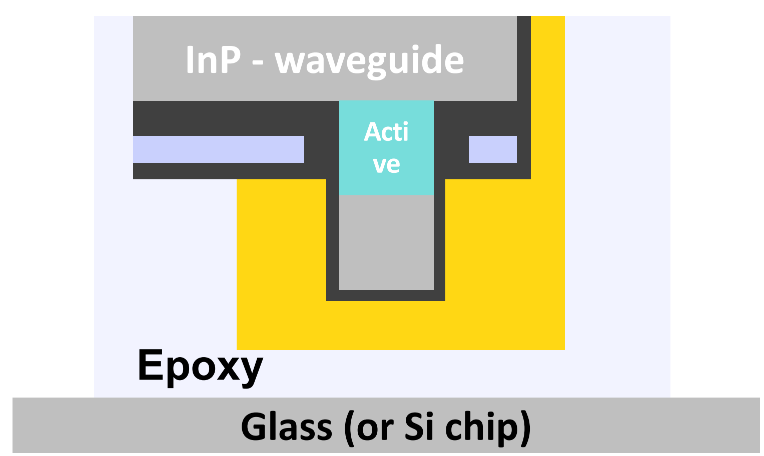
Thrust 1: Optimization of LED stack

Thrust 2: Layer transfer technology for heterointegration

Desired Growth Stack



Final Device Design



Etch stop optimization

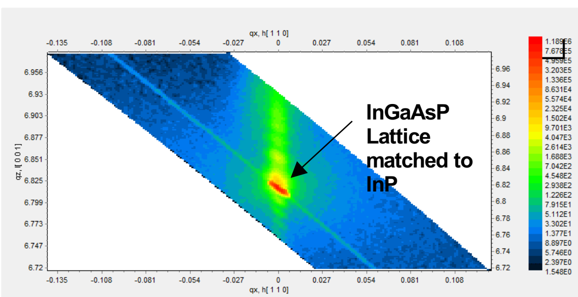
Calibration of InGaAsP (λ =1200nm) etch stop

Assuming distribution coefficient remain constant with incremented flowrates
Flow rates were adjusted accordingly to achieve target composition of $In_{0.729}Ga_{0.271}As_{0.585}P_{0.415}$

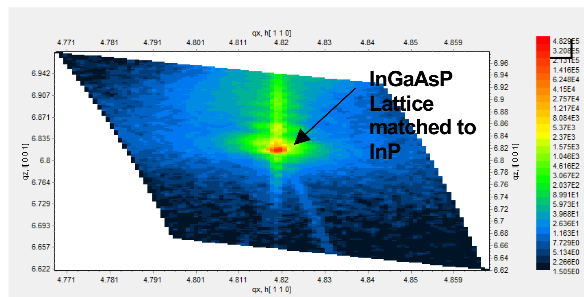
TMIn (mol/min)	TMGa (mol/min)	PH3 (mol/min)	AsH3 (mol/min)
6.56E-5	1.758E-5	1.35E-2	5.960E-4

XRD RSM analysis

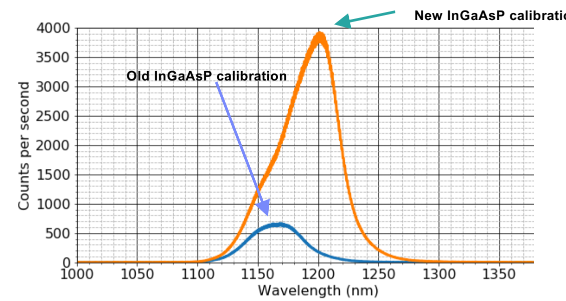
[004] reciprocal lattice index



[224] reciprocal lattice index



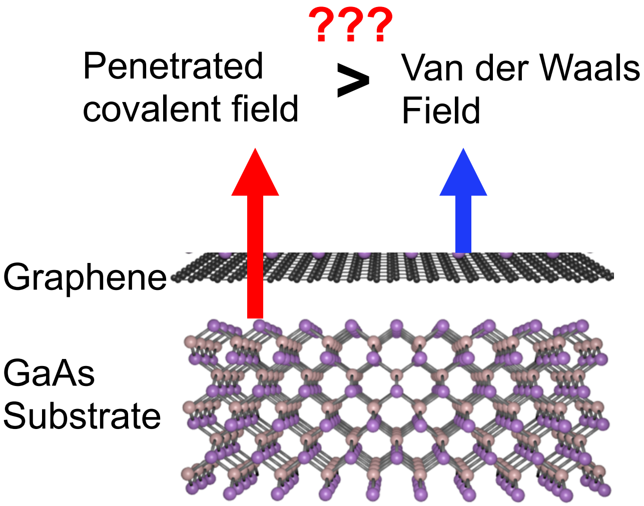
PL Spectra

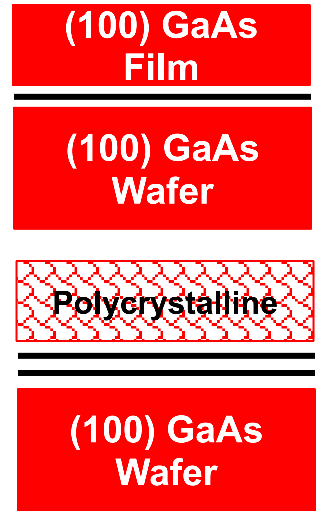


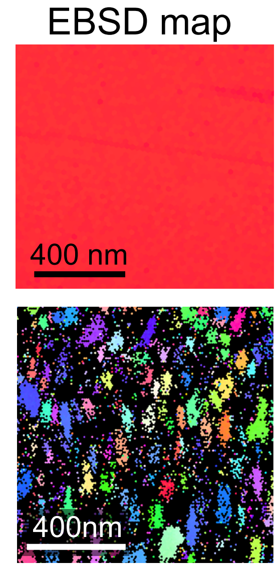
new λ_{peak} = 1202 nm

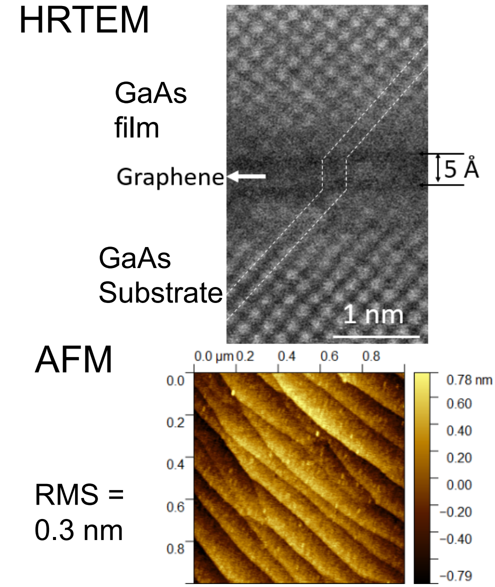
Negligible shift in the distribution coefficient was observed, target composition was achieved in updated recipe
Increase in PL peak intensity was attributed lower contamination in InGaAsP layer due to prior effort to decontaminate chamber before growth

Strategy to interointegrate nano-LED on Si: Remote epitaxy



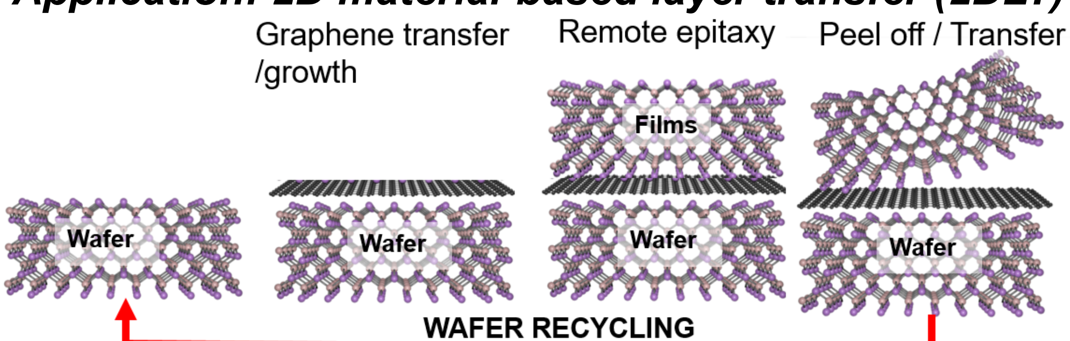


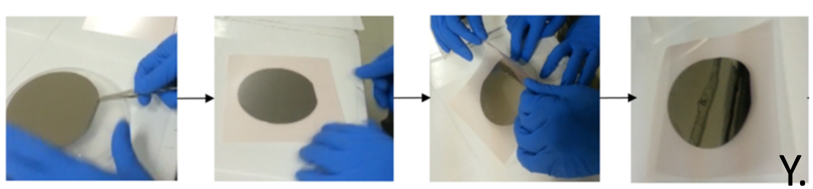




Perfect single-crystalline planar films can be grown on 2D materials

Application: 2D material-based layer transfer (2DLT)





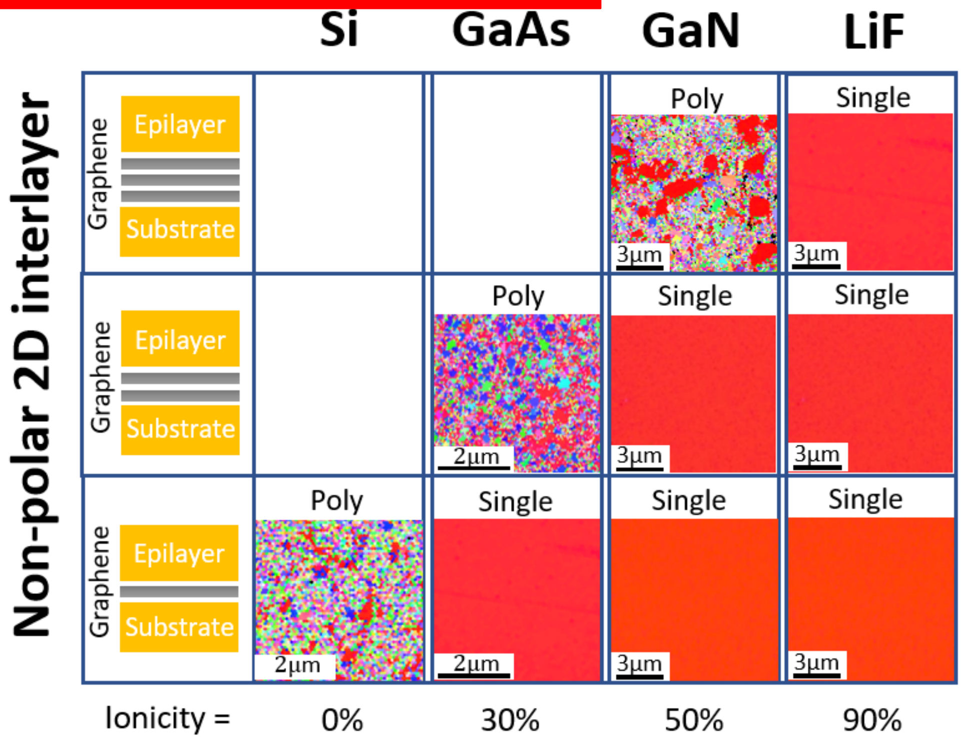
Monolayer graphene + Wafer

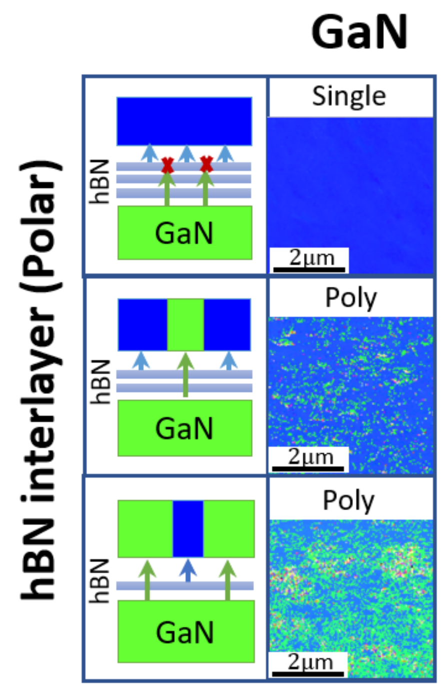
= Copy Machine (Film producer)

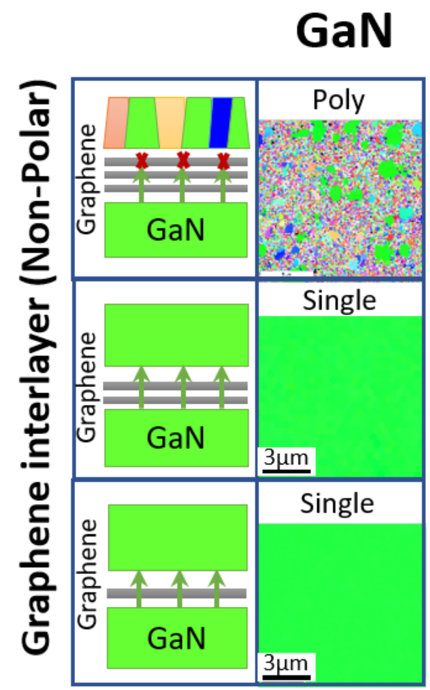
Y. Kim et al., and J. Kim., ***Nature*** 544, 340 (2017)

Polarity governs remote atomic interaction through 2D materials

DFT thermodynamic calculation

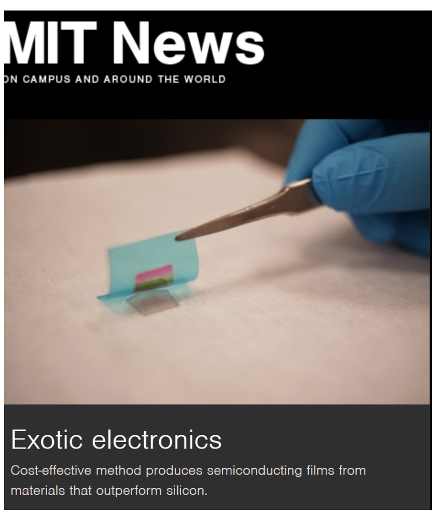






Polarity of 3D materials determines field penetration

Polarity of 2D materials determines field screening



W. Kong,…and J. Kim*, ***Nature Materials***, Vol. 17, 335 (2018)

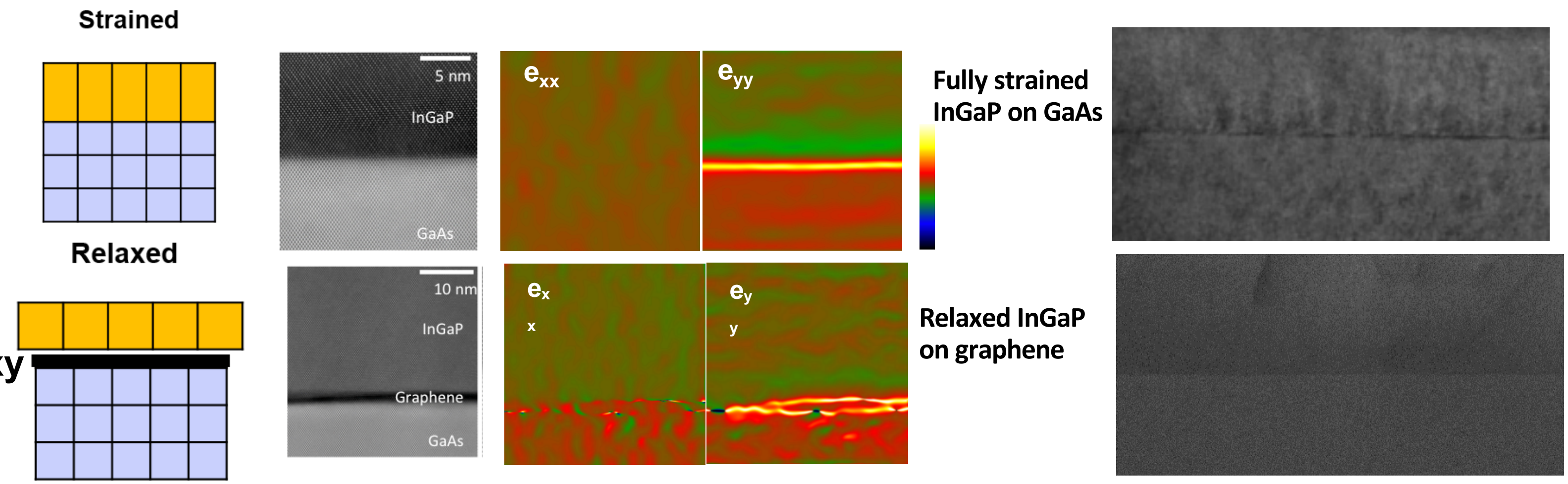
S. Bae…, and J. Kim*, ***Nature Materials***, Vol 18, 550 (2019)

Remote heteroepitaxy: Dislocation-free heteroepitaxy

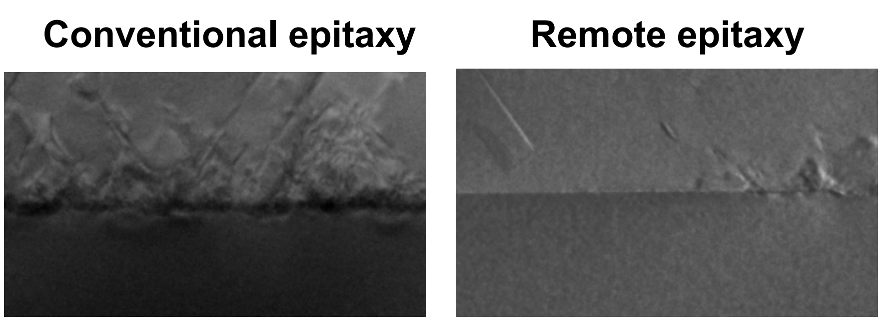
1% strained InGaP on GaAs

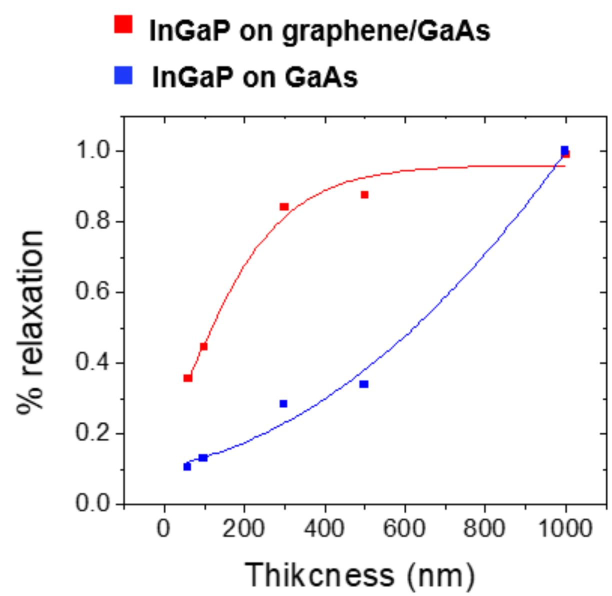
Conventional Epitaxy

Remote epitaxy on graphene



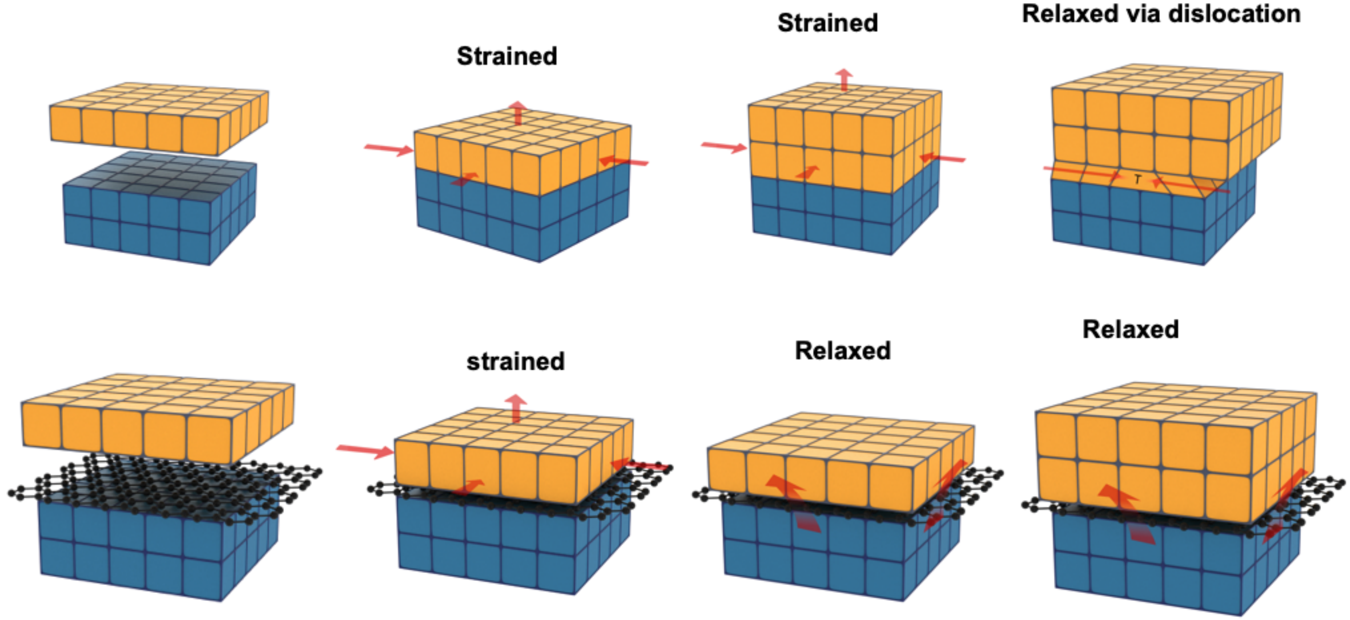
4% strained GaP on GaAs

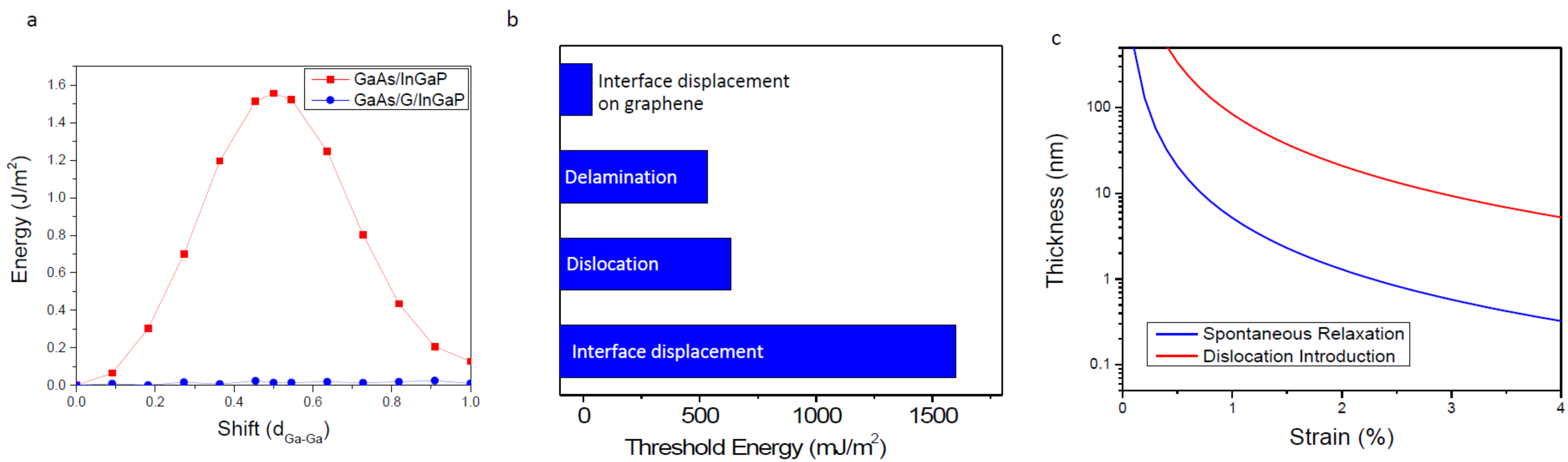




Bae et al, and Kim*, ***Nature Nanotechnology*** (2019) *under revision*

New critical thickness on slippery graphene





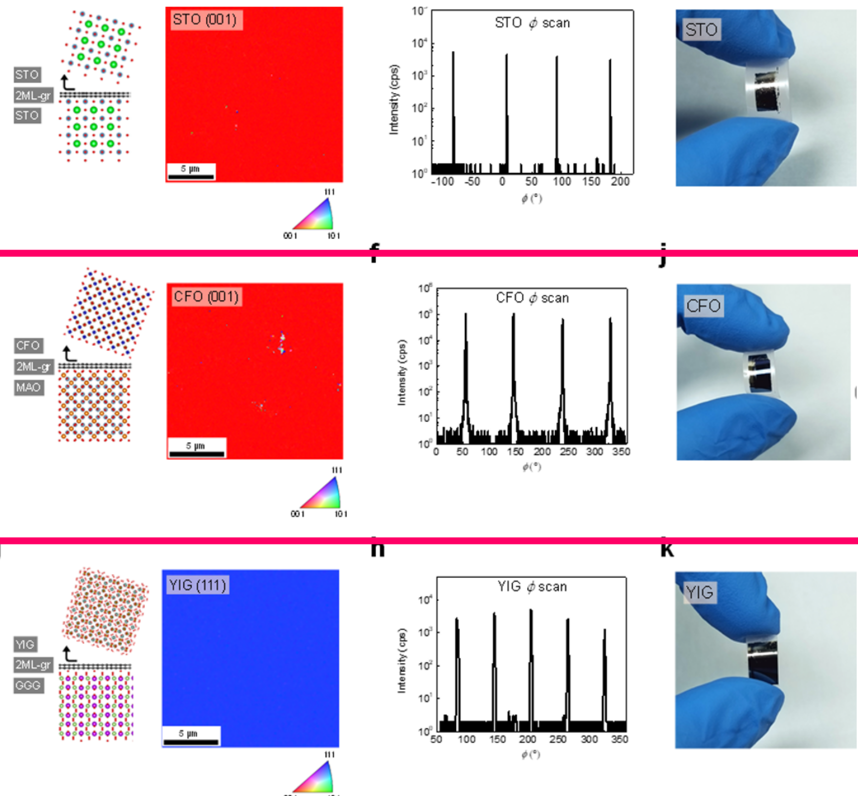
Bae et al, and Kim*, ***Nature Nanotechnology*** (2019) *under revision*

Remote epitaxy for complex oxides

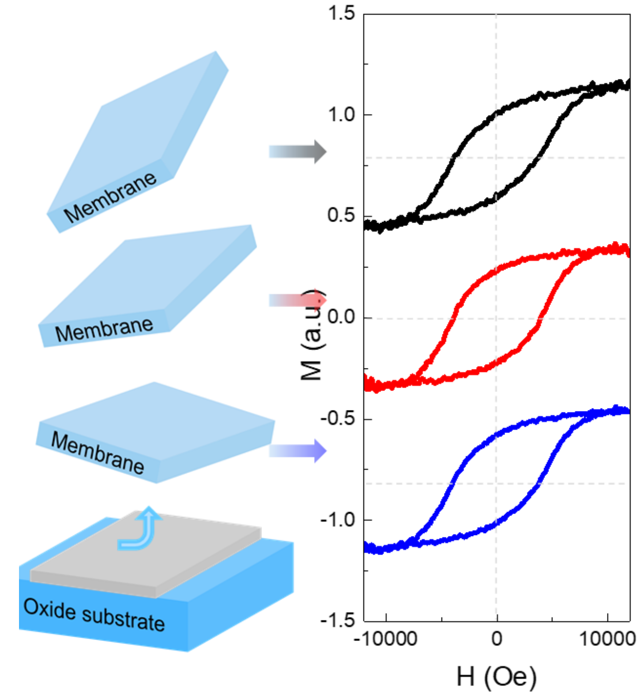
Pervoskite
$SrTiO_3$ (STO)

Spinel
$CoFe_2O_4$ (CFO)

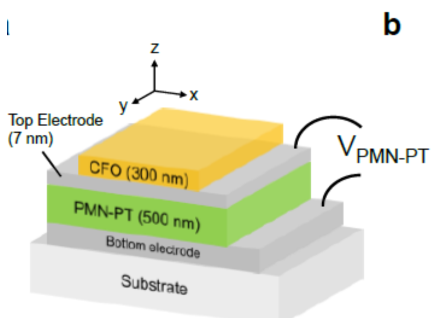
Garnet
$Y_3Fe_5O_{12}$ (YIG)

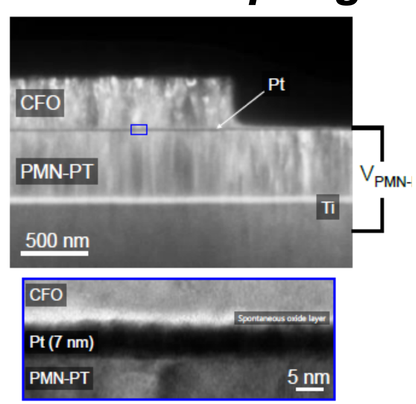


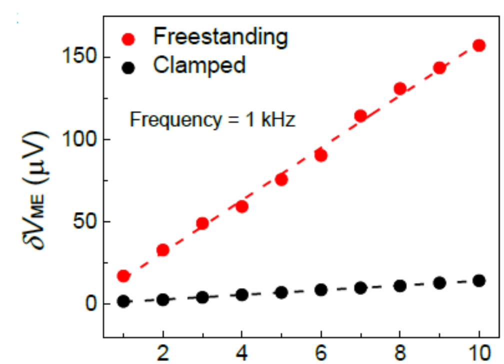
Wafer reusability



Heterointegration: Magnetoelectric coupling of freestanding oxides (PMNPT+CFO)

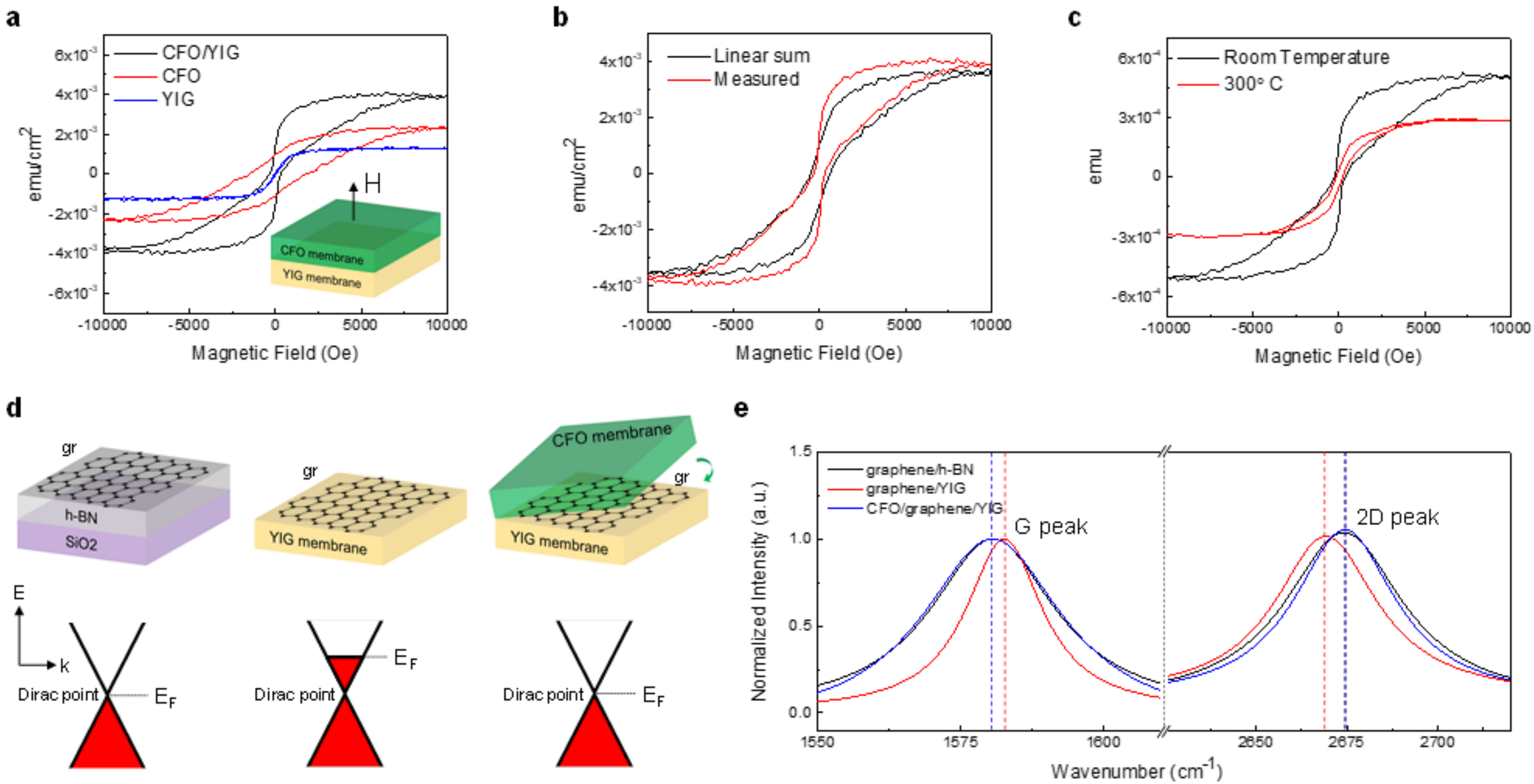






Heterointegration of complex oxides

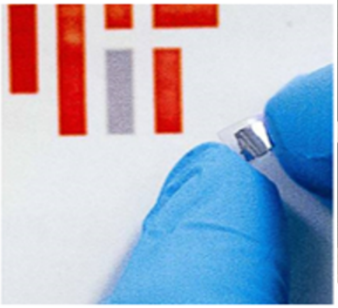
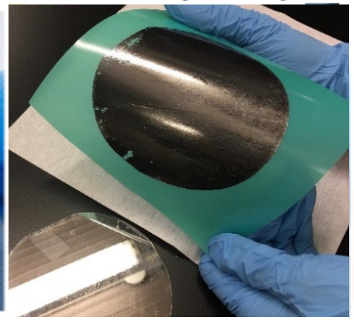
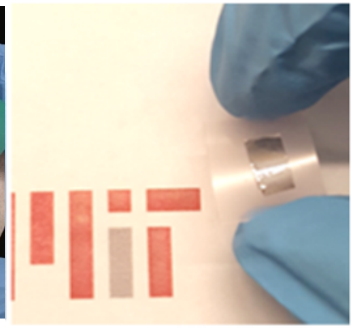
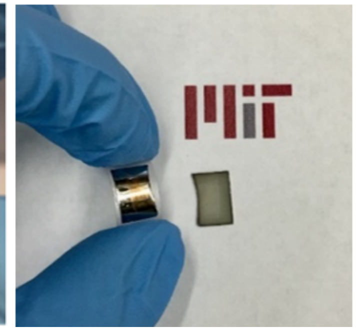
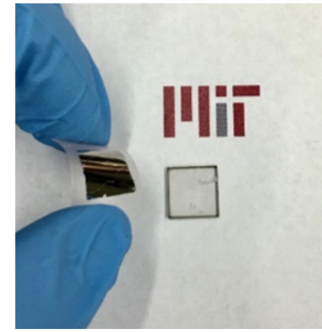
Magnetostatic + electrical coupling of freestanding oxides (YIG + CFO)



Kum et al, and Kim*, ***Nature*** (2019) *under revision*

Potential of remote epitaxy

GaAs (III-V)	GaN (III-N)	InP (III-V)	$SrTiO_3$ (Oxide)	LiF (fluoride)

MicroLEDs

High efficiency PV Transistor	Wireless system Power system	Photodetector	Piezoelectric sensor	Optical waveguide Battery

Monolayer graphene + Wafer

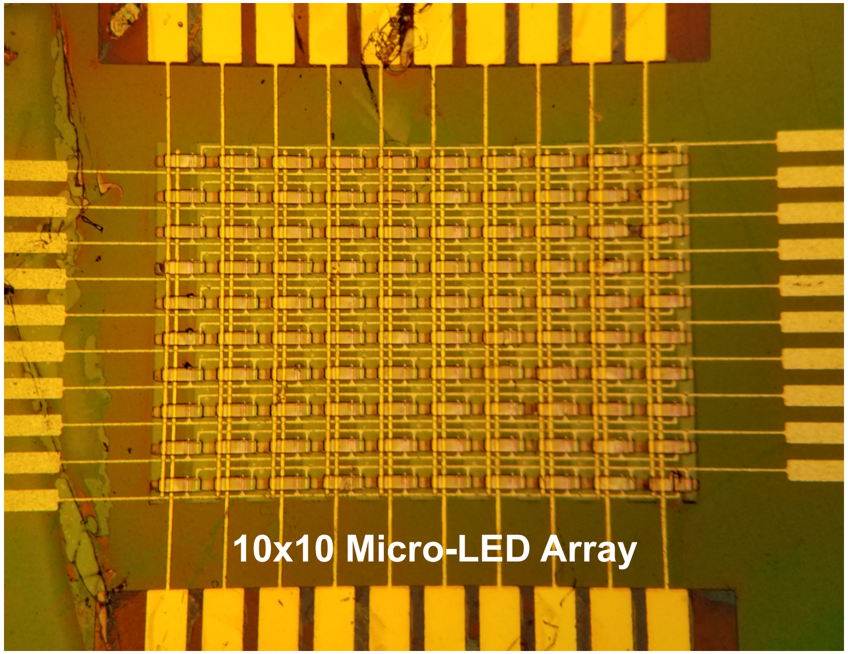
= Copy Machine (Film producer)

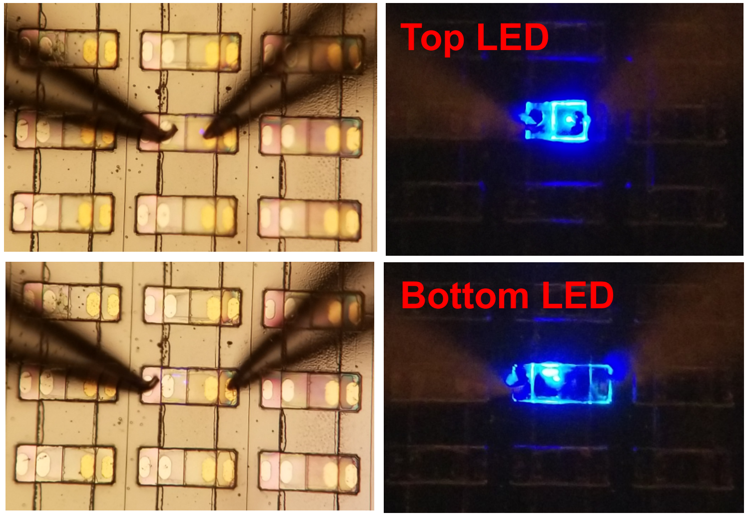
Self-powered/analyzed electronic wireless system

- **AI chip**
- **Wireless signal**
- **Sensors**
- **Micro-battery**
- **Solar cells**

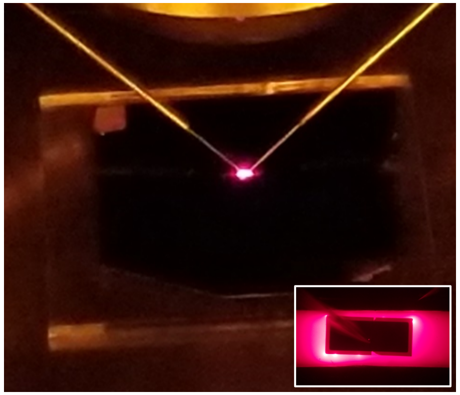
↑ sunlight

Micro-LED Display



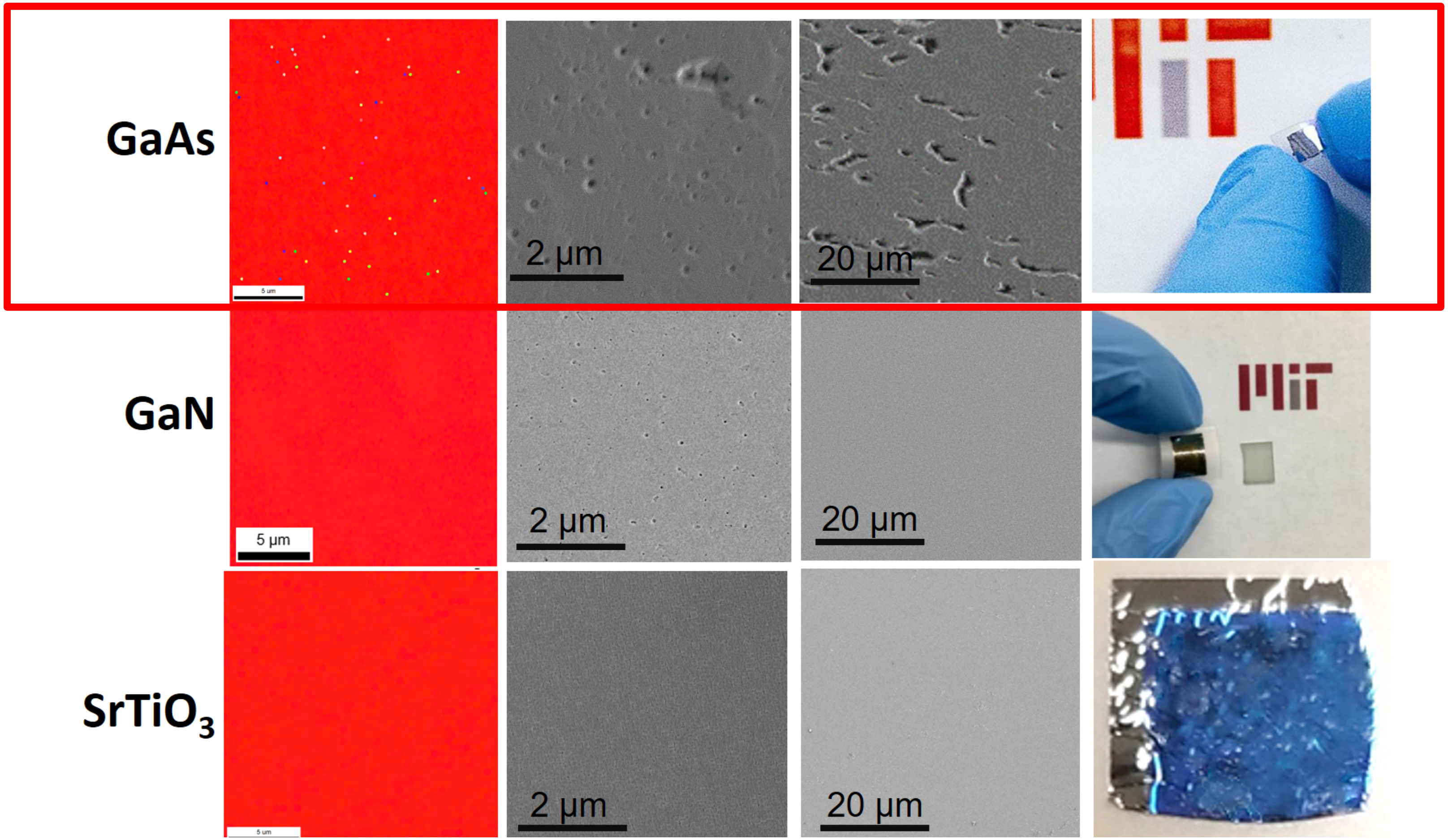


GaN LED



AlInGaP LED

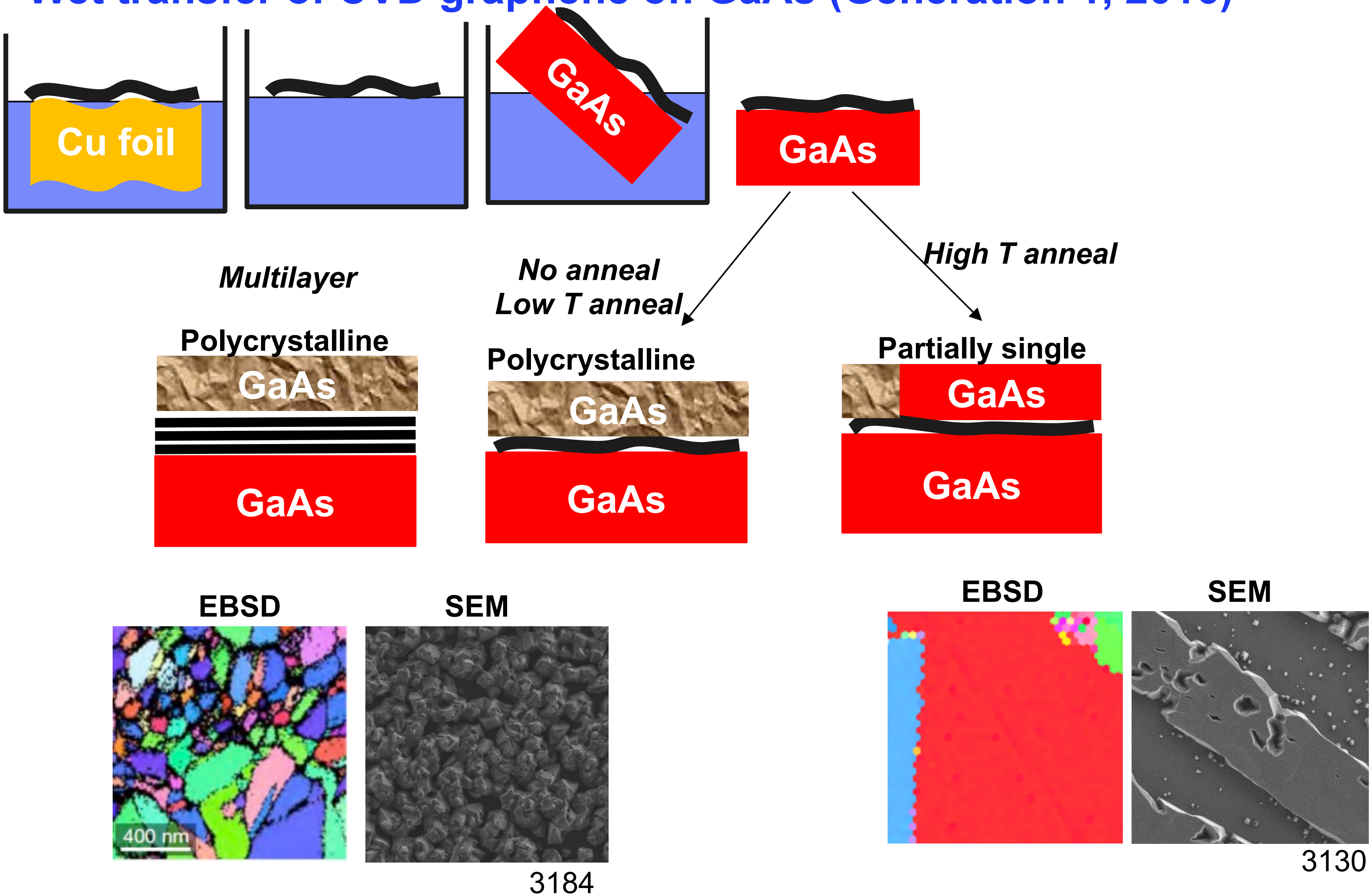
Challenges in remote epitaxy



1. **Weak field penetration due to 30% ionicity**
2. **Native oxide formation during graphene transfer**

Key to succeed on remote epitaxy: Graphene transfer

Wet transfer of CVD graphene on GaAs (Generation 1, 2016)

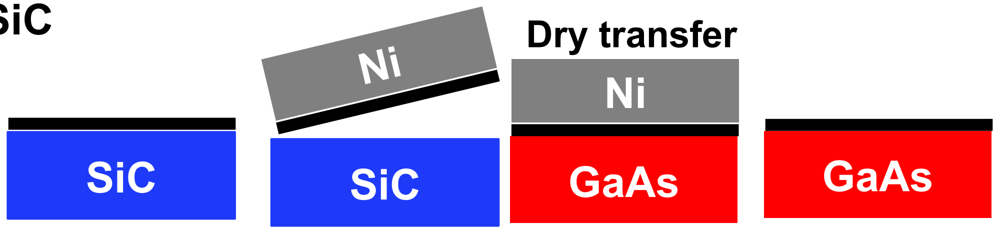


Crystallinity of GaAs completely depends on graphene transfer methods
CVD graphene wet transfer does not allow complete single-crystallinity

Key to succeed on remote epitaxy: Graphene transfer

Dry transfer (LRGT) of epitaxial graphene on GaAs (Generation2, 2017 Nature)

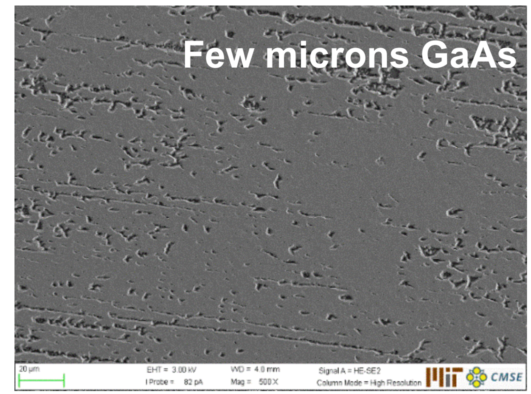
Forming "epitaxial graphene" on SiC



Single-crystalline

EBSD

SEM



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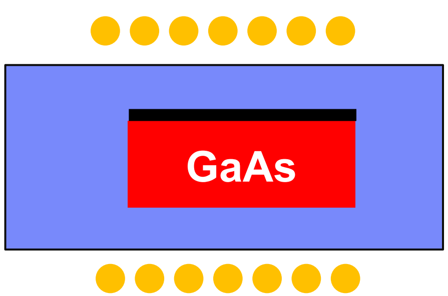
Single-crystallinity secured if epitaxial graphene is dry transferred

Growth of graphene on GaAs (Generation 3, since 2018)

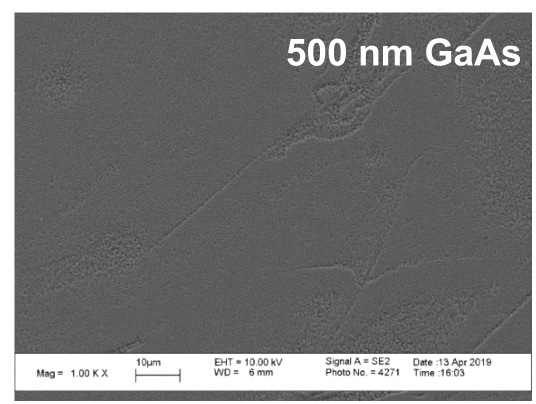
Direct growth in furnace



Single-crystalline

EBSD

SEM



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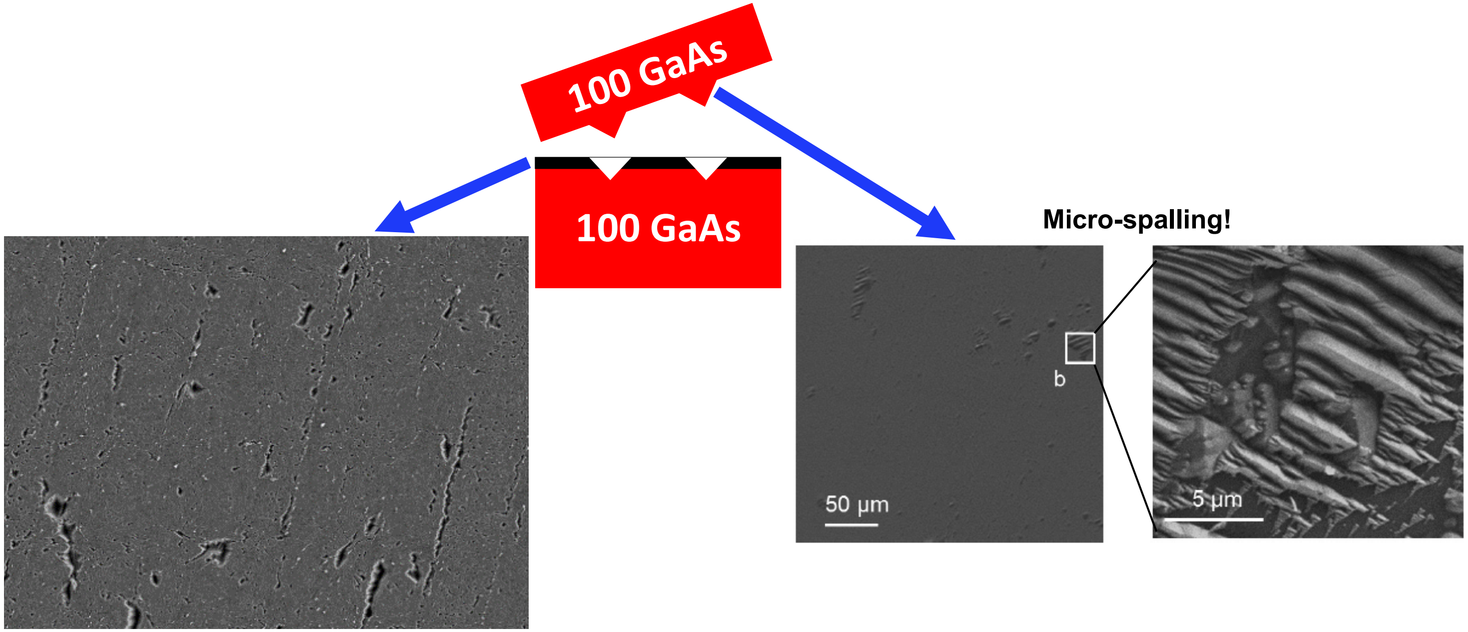
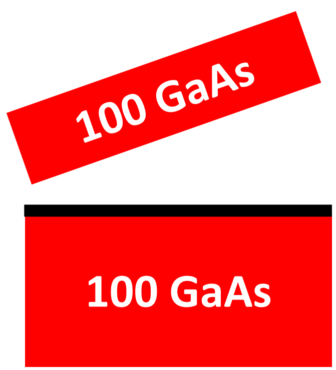
Grown graphene improves morphology

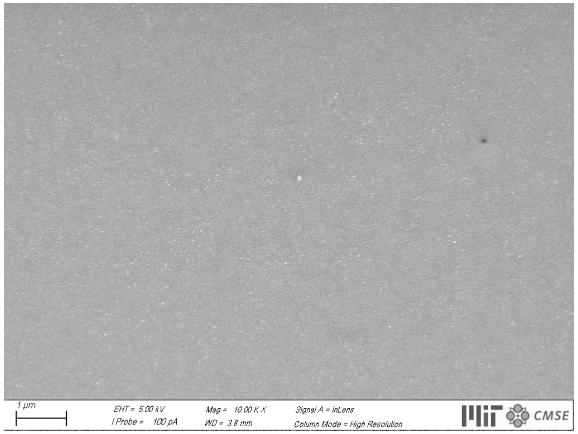
Wafer reusability: Manual graphene transfer creates holes in graphene



Defect (holes) formation after graphene transfer
→ Micro-spalling marks on GaAs form after 2DLT
→ Challenging to perform 2nd graphene transfer on GaAs wafers

Direct growth of graphene eliminates holes

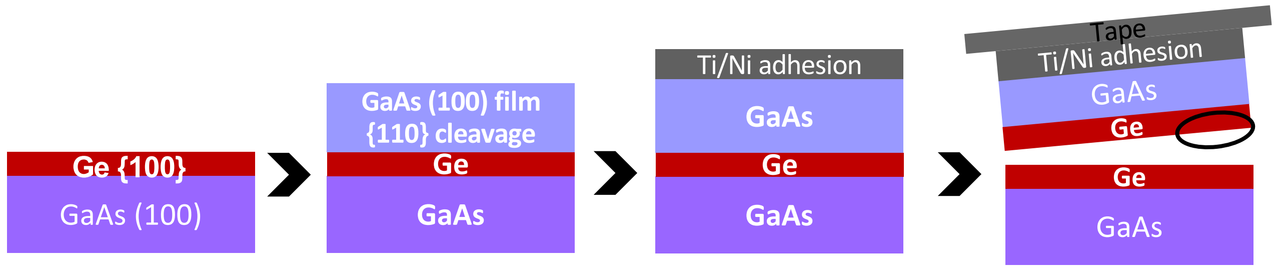


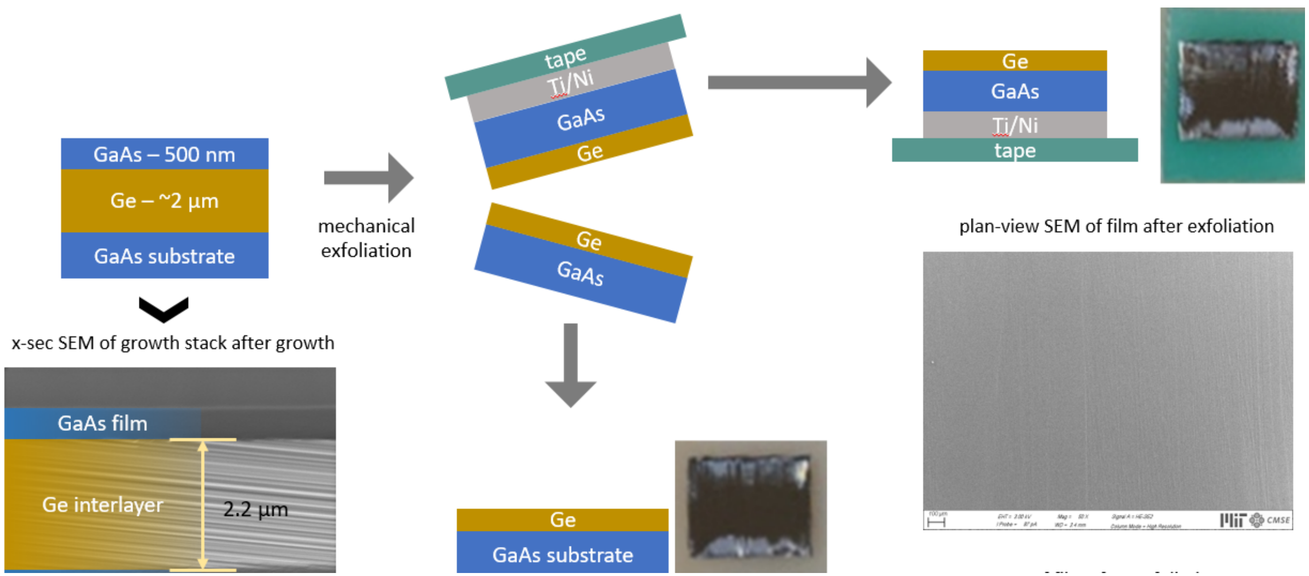


Plan B: Graphene-free mechanical transfer

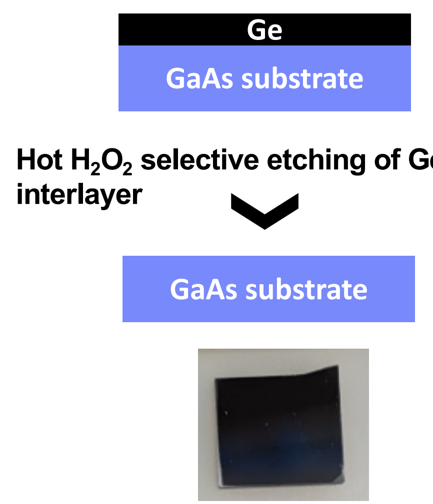
Cleavage plane assisted exfoliation

materials	Cleavage Plane
Si	{111}
Ge	{100}
GaAs	{110}
GaSb	{100}
InP	{100}
InAs	{100}



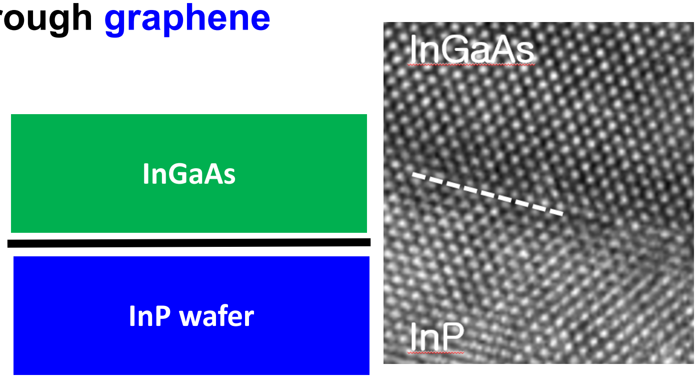


Substrate re-usability



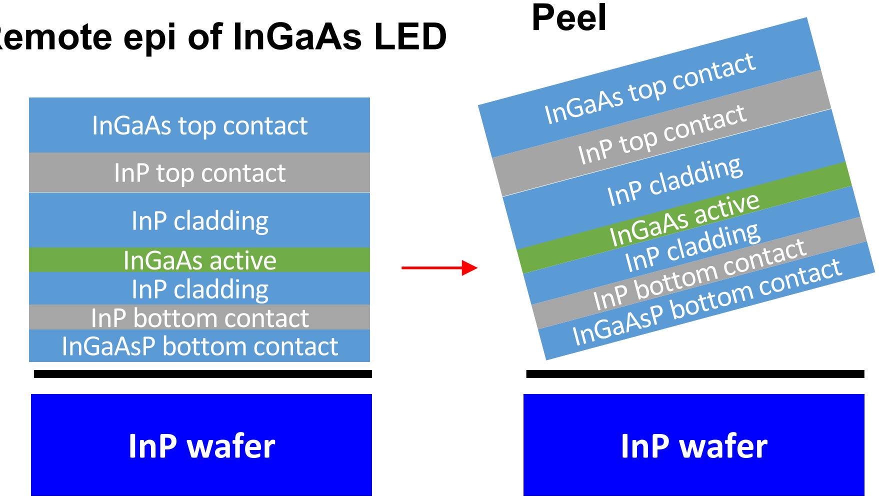
III-V optoelectronics on Si

Remote epitaxy of InGaAs through graphene



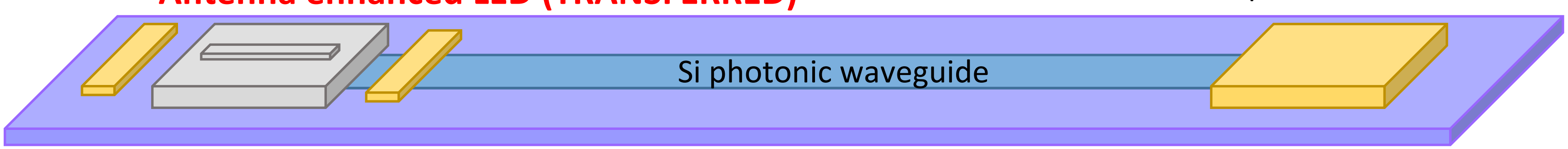
Remote epi of InGaAs LED

Peel



Antenna enhanced LED (TRANSFERRED)

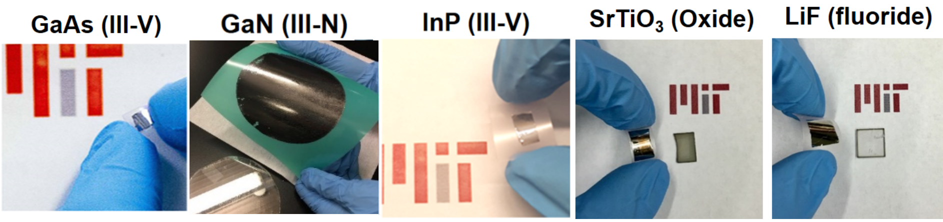
photodetector



With Prof. Ming Wu

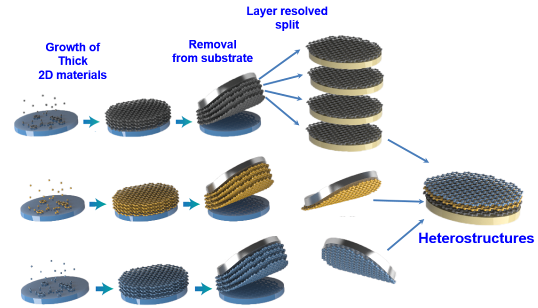
Nanoelectronics Group at MIT

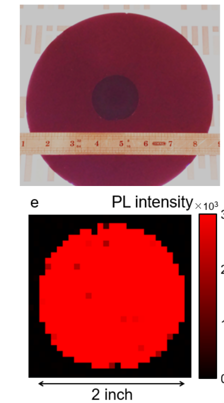
Freestanding semiconductors



Nature (2017), Nature Materials (2018), Nature Materials (2019)
Nature Nanotech (2019)

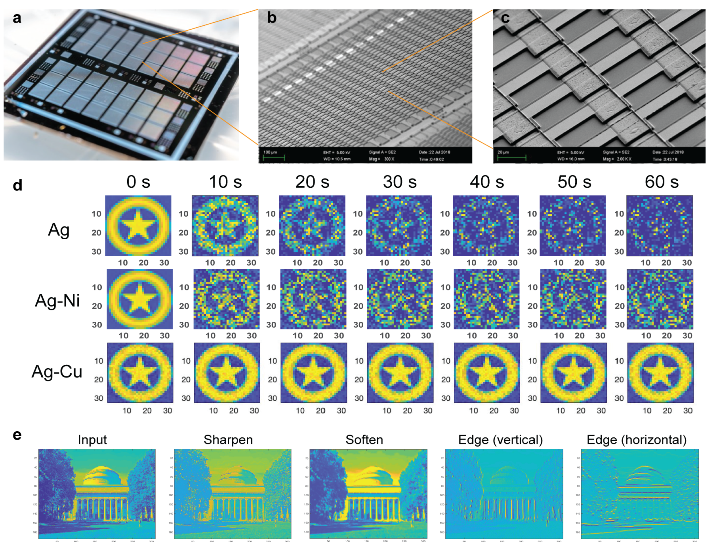
Wafer-scale 2D Materials Group





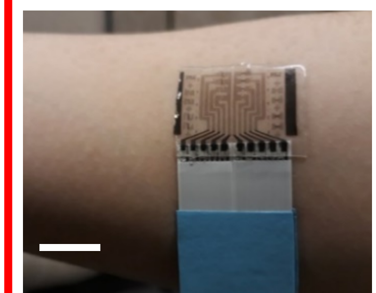
Science (2018)

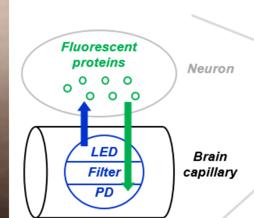
AI hardware

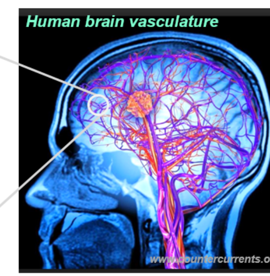


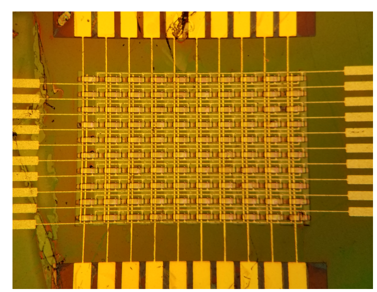
Nature Materials (2018)

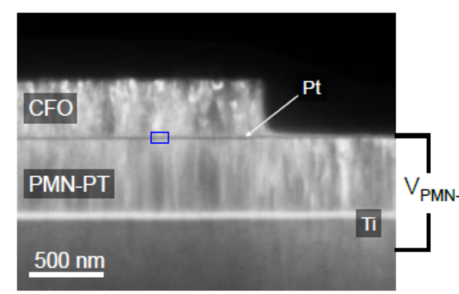
Heterointegrations











Nature (2019)