



Massachusetts
Institute of
Technology

2D material based layer transfer

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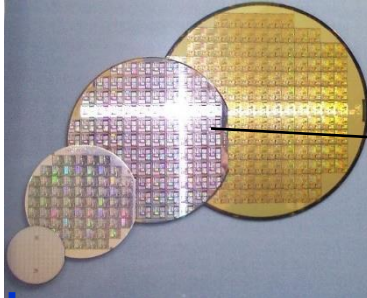
<http://jeewanlab.mit.edu>

Major bottleneck for advancing semiconductor technology

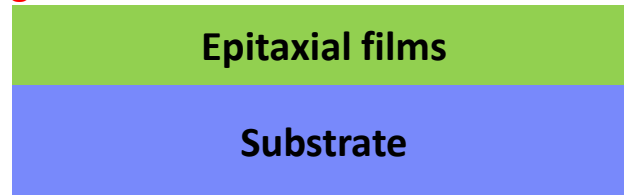
Substrate: Essential building block to form Electronic/optoelectronic devices

Epitaxial growth: Process for forming device film structures on the substrate

FETs, LEDs, Lasers, Detectors

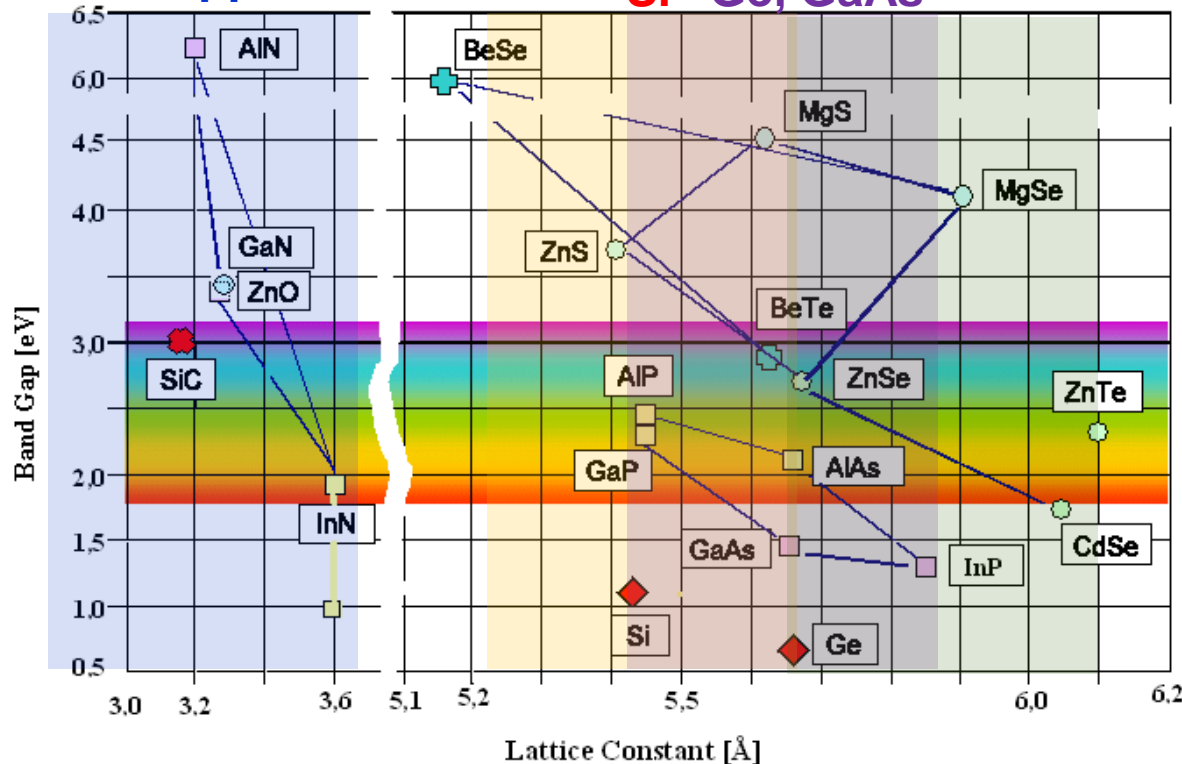


Epitaxy of single-crystalline films is required on given available substrates



SiC, Sapphire

Si Ge, GaAs InP



Price:

SiC > InP > GaAs > Ge >>> Si

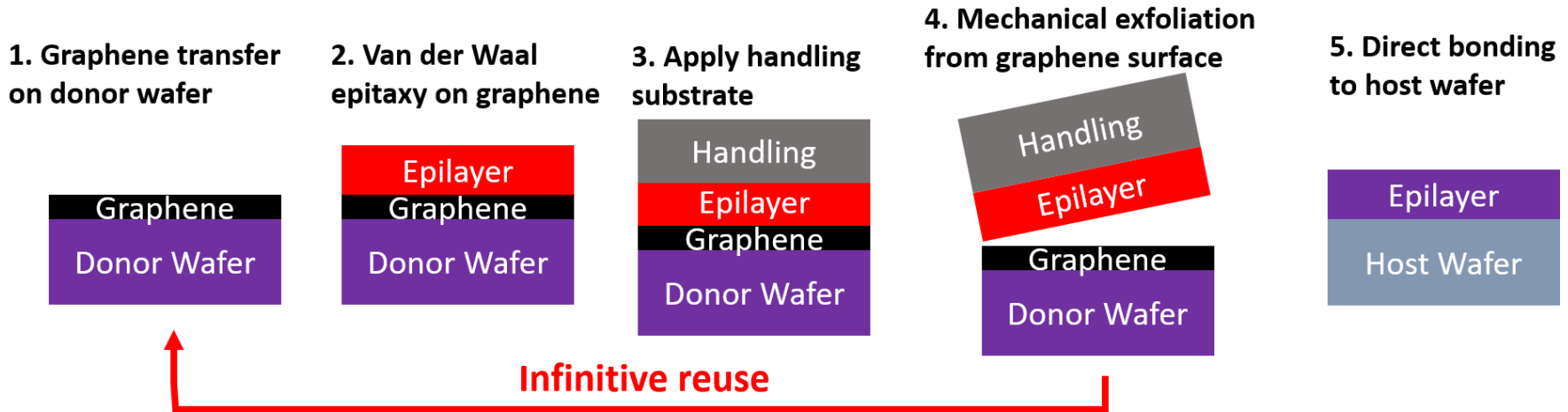
Limited application

Lattice:

InP > GaAs/Ge > Si > SiC

Defect generation

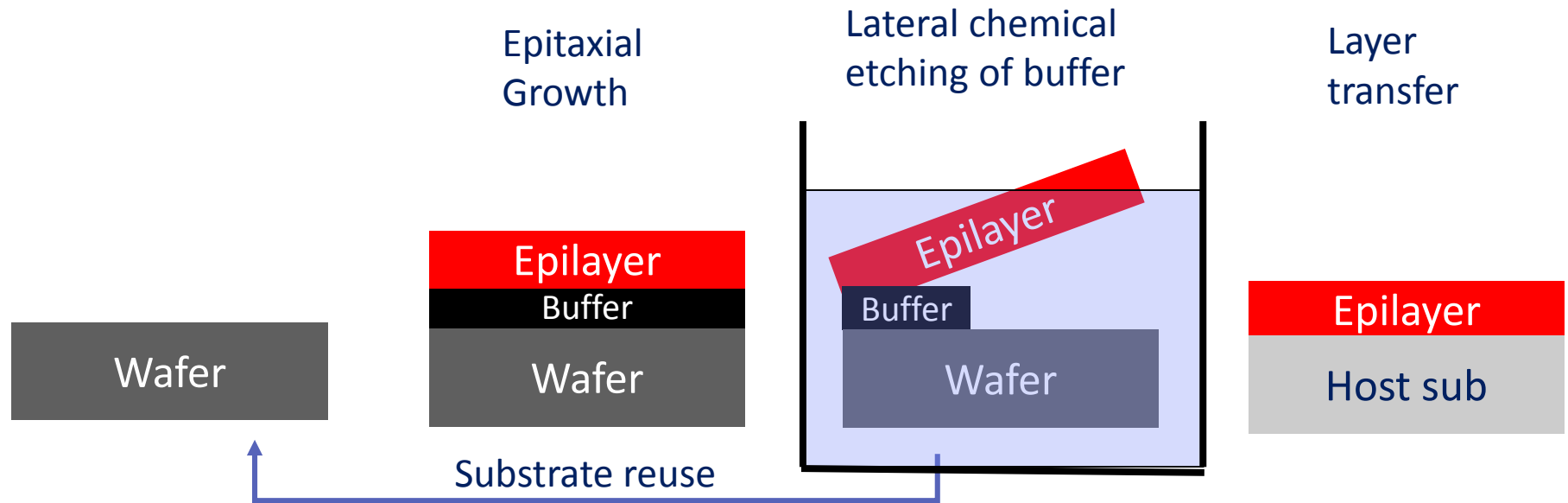
2D material based layer transfer (2DLT)



■ sp^2 -bonded graphene: No broken bonds on the surface

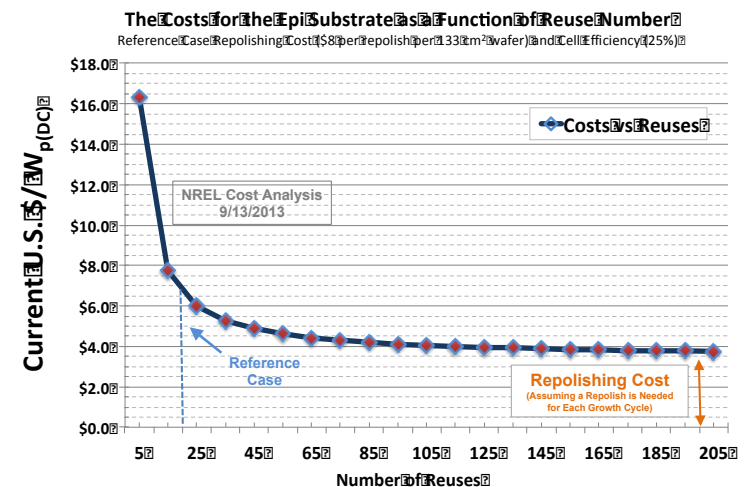
- ❑ Precise release from graphene
- ❑ Post-release treatment NOT required
- ❑ **1 sec** release due to weak interaction
- ❑ Universal for any materials

Chemical lift-off (Epitaxial lift-off, ELO)

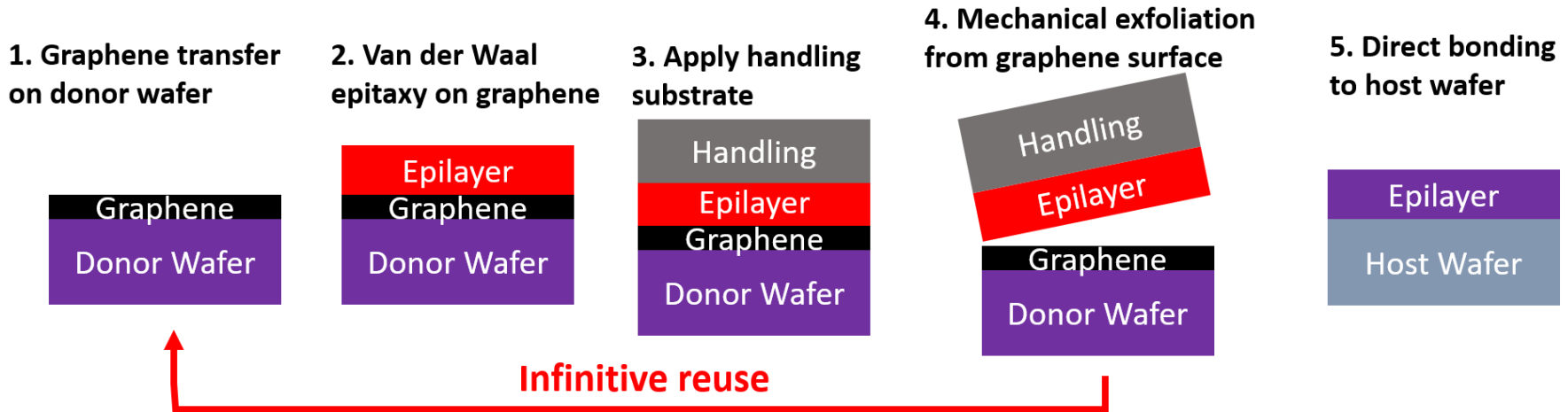


- **Pro: Control of release interface**
- **Cons:**
 - ❑ Post-treatment required
 - ❑ Slow release
 - ❑ Limited application mainly for GaAs & InP

For PV applications



Graphene-based layer transfer (GBLT)

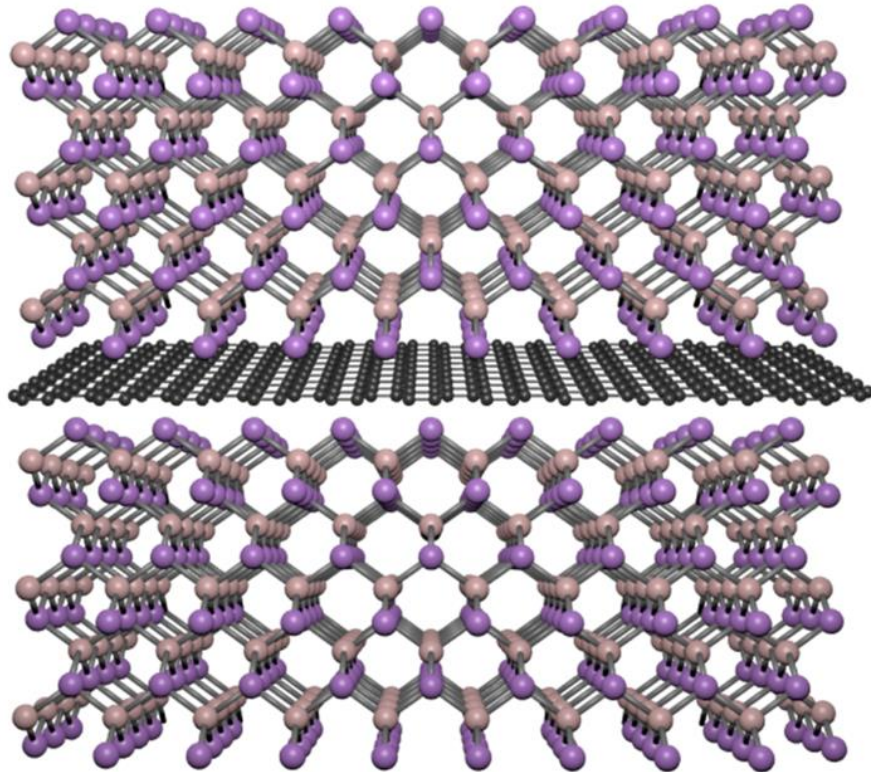


■ sp^2 -bonded graphene: No broken bonds on the surface

- ❑ Precise release from graphene
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- ❑ Universal for any materials

Meet all requirements

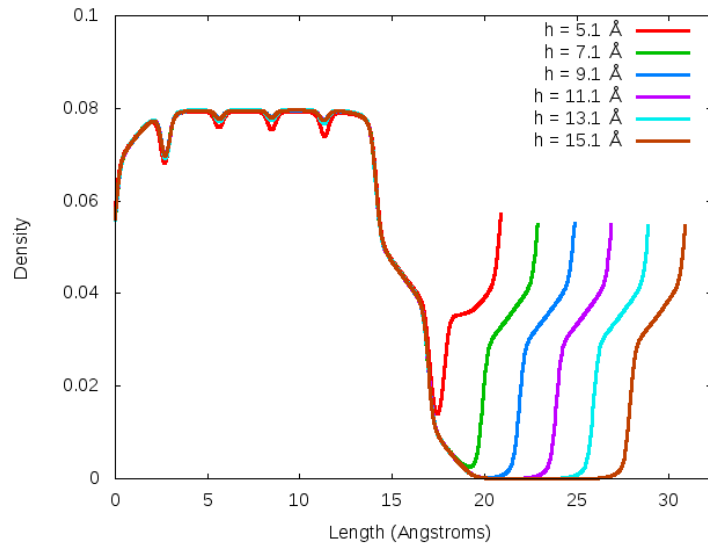
Monolayer graphene transparency for epitaxial growth - Remote homoepitaxy



Y. Kim, S. Cruz, J. Kim et al., *Nature*, **COVER** (2



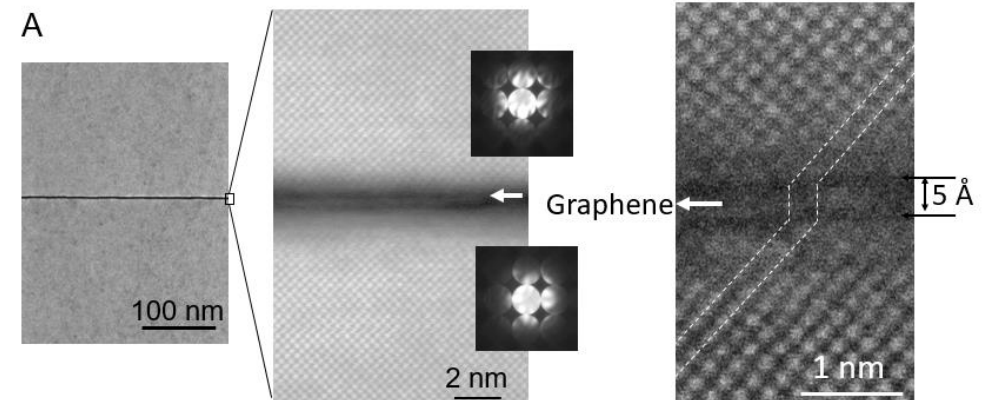
DFT calculation



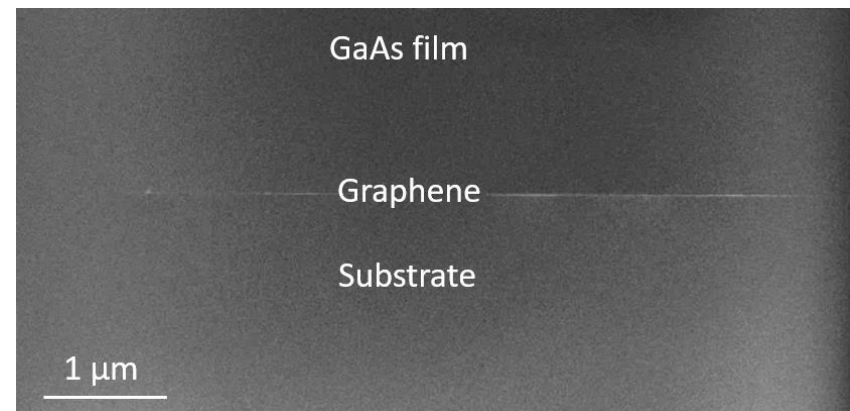
Critical interaction gap: 1 nm

In collaboration with Prof. Kolpak

HRTEM



Dark field XTEM: Strain field



No sign of dislocation

Remote homoepitaxy is possible through graphene

Y. Kim, S. Cruz, J. Kim et al., *Nature* (2017)

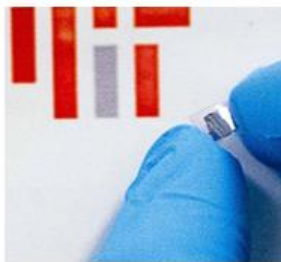
Universality of 2DLT (MIT)

Growth of single-crystalline GaN, GaAs, InP, GaP, Ge on graphene

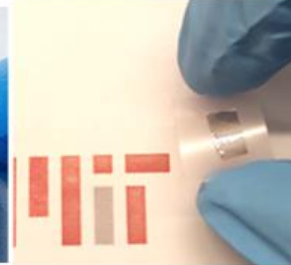
Periodic Table of the Elements

1 IA H Hydrogen 1.00794	2 IIA He Helium 4.002602																	18 VIIIA Ar Argon 39.948	19 VIIIA K Potassium 39.0983	20 IIA Ca Calcium 40.078											36 Kr Krypton 83.798	37 IB Rb Rubidium 85.4678	38 IIA Sr Strontium 87.62											54 Xe Xenon 131.29	55 IB Cs Cesium 132.90545	56 IIA Ba Barium 137.327											86 Rn Radon 222	87 IB Fr Francium [223]	88 IIA Ra Radium [226]											118 Uuo Ununoctium [289]	117 VIIA Uus Unseptium [288]	116 VIA Lv Livermorium [293]	115 VA Uup Unpentium [288]	114 IVA Fl Flerovium [289]	113 IIIA Uut Untrium [288]	80 Hg Mercury 200.59	79 Au Gold 196.966569	78 Pt Platinum 195.083	77 Ir Iridium 192.222	76 Os Osmium 190.23	75 Re Rhenium 186.207	74 W Tungsten 183.84	73 Ta Tantalum 180.94788	72 Hf Hafnium 178.49	71 Zr Zirconium 91.224	70 Y Yttrium 88.90584	59 Sc Scandium 44.955912	58 Ce Cerium 140.12	57 La Lanthanum 138.90547	56 Ba Barium 137.327	55 Cs Cesium 132.90545	38 Sr Strontium 87.62	37 Rb Rubidium 85.4678	19 K Potassium 39.0983	12 Zn Zinc 65.38	11 Cd Cadmium 112.411	10 Ag Silver 107.8682	9 Pd Palladium 106.90509	8 Rh Rhodium 102.90550	7 Ru Ruthenium 101.07	6 Fe Iron 55.845	5 Co Cobalt 58.933195	4 Ni Nickel 58.6934	3 Cu Copper 63.546	2 Mn Manganese 54.938045	1 Cr Chromium 51.9961	24 V Vanadium 50.9415	23 Ti Titanium 47.88	22 Sc Scandium 44.955912	21 Ca Calcium 40.078	20 K Potassium 39.0983	19 Ar Argon 39.948	18 Cl Chlorine 35.45	17 S Sulfur 32.06	16 P Phosphorus 30.973762	15 Si Silicon 28.0855	14 Al Aluminum 26.9815385	13 B Boron 10.811	12 C Carbon 12.0107	11 N Nitrogen 14.00643	10 O Oxygen 15.999	9 F Fluorine 18.9984032	8 Ne Neon 20.1797	2 He Helium 4.002602	1 H Hydrogen 1.00794
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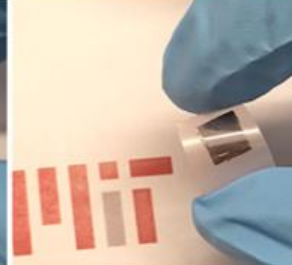
(a) GaAs (100)



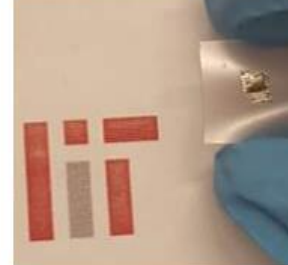
(b) InP (100)



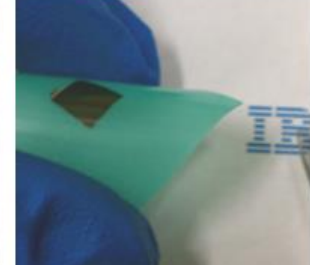
(c) GaP (100)



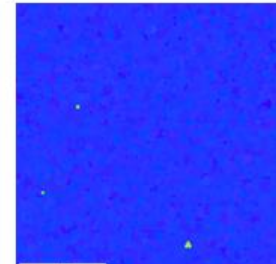
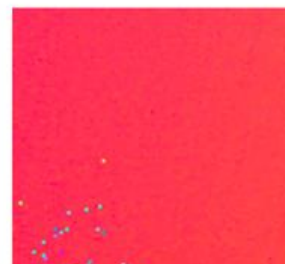
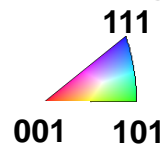
(d) GaAs (111)



(e) GaN (0001)



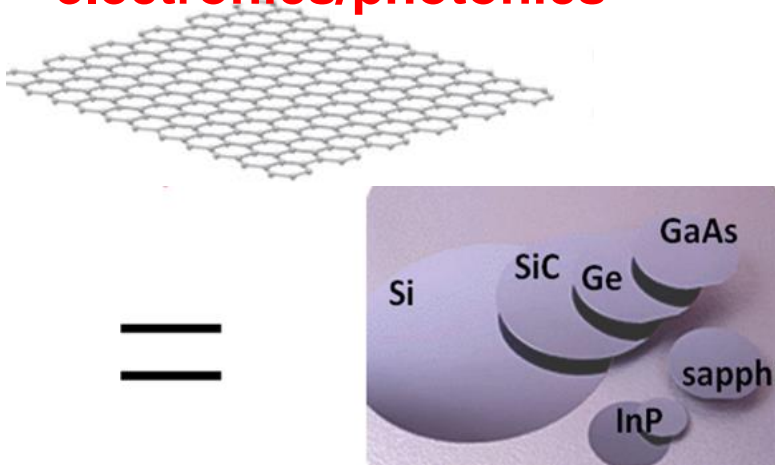
EBSD
mapping



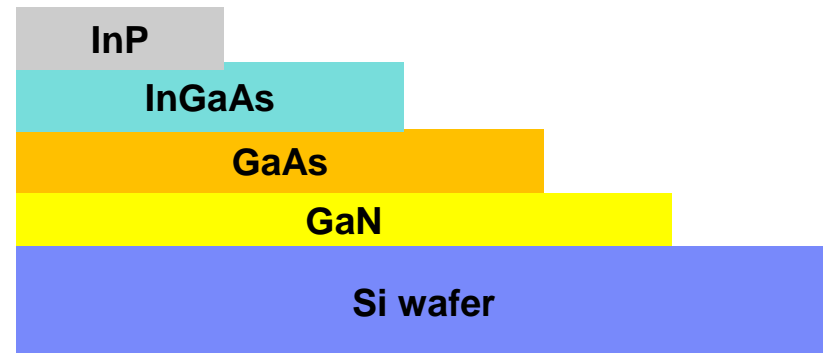
Role of graphene

- Release layer for any semiconductors
- Dislocation-reducer/filter
- Release layer → 1sec release
- Wafer Surface protection → infinite reuse

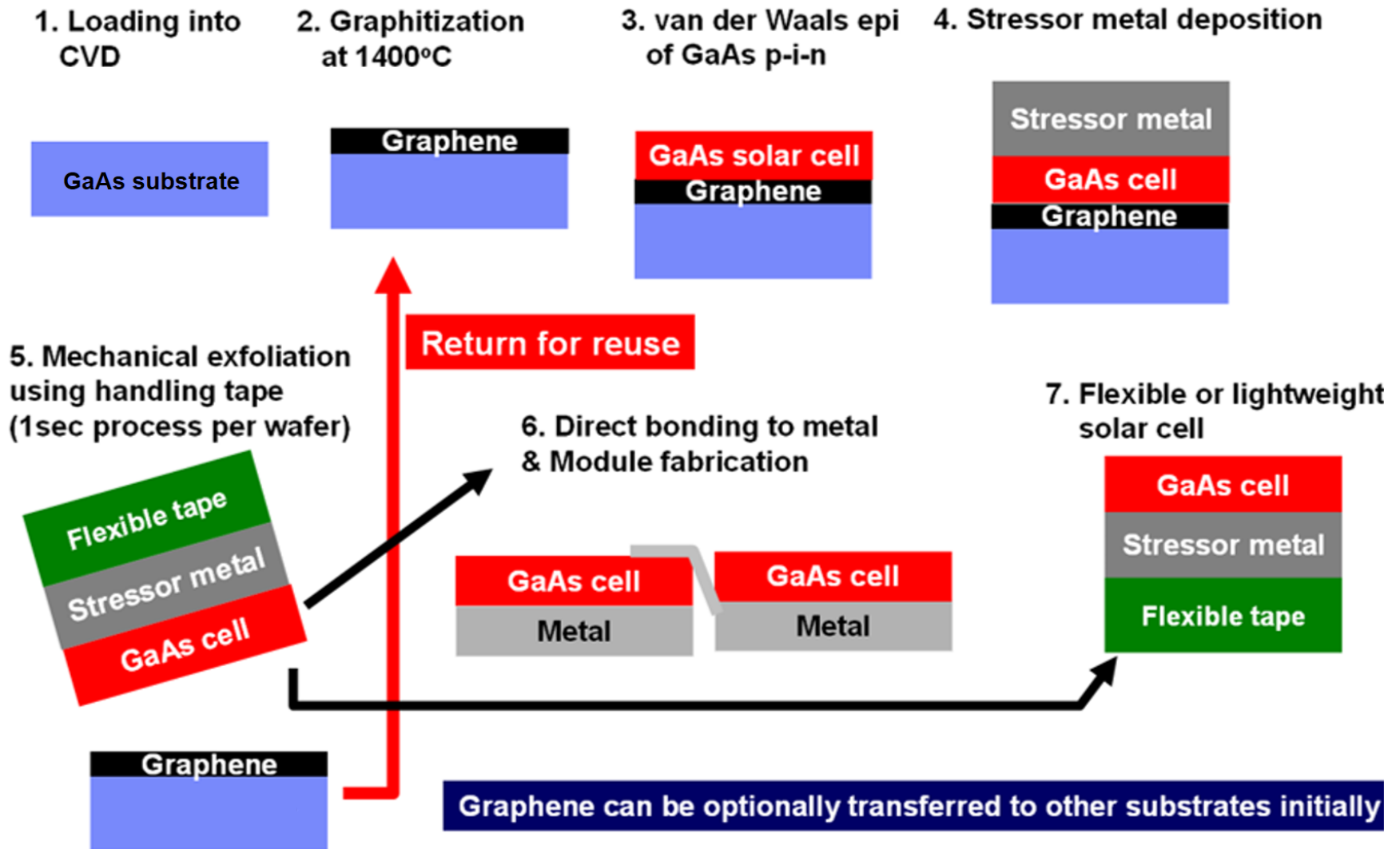
Wide application of non-Si electronics/photronics



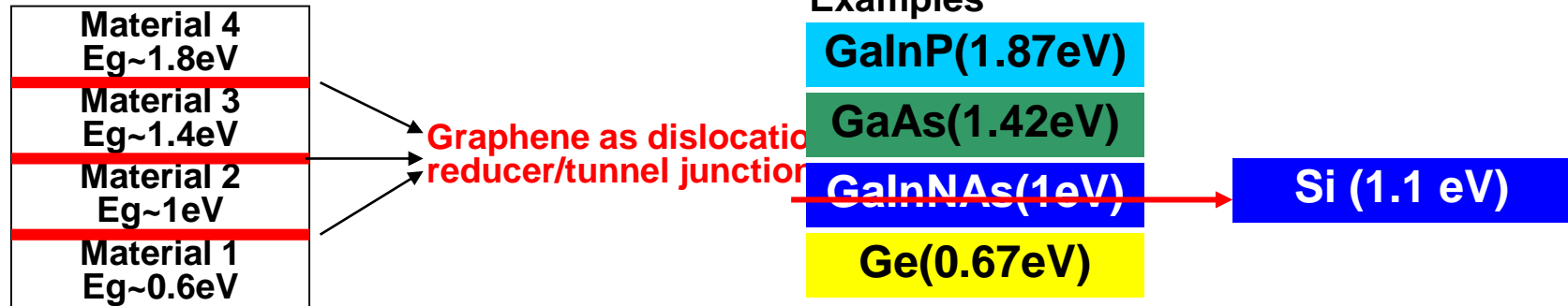
Enabled heterointegration



Implication for PV technology

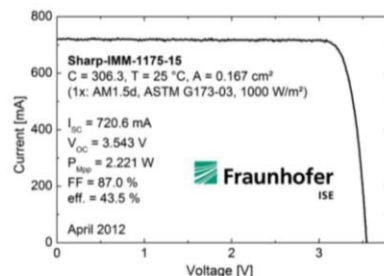
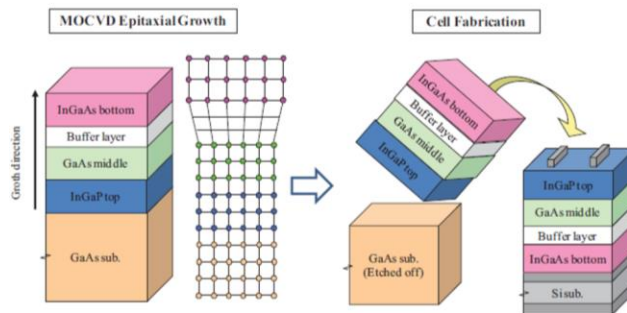


III-V multijunction solar cells for E_g oriented design



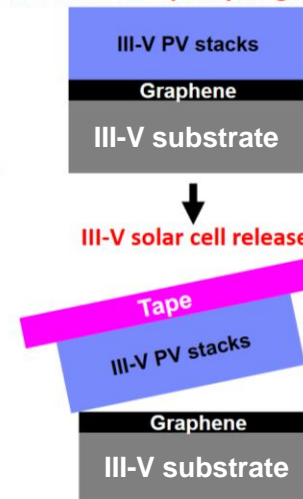
Multiple fabrication high efficiency solar cells reusing graphene

40% solar cell process



Graphene-based III-V layer transfer

III-V solar cell epitaxy on graphene



Implication for magnetoelectric coupling

Graphene transfer



Epitaxy of Piezoelectric materials



Exfoliation of Piezoelectric materials

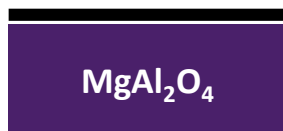


Bonding of freestanding Piezomaterials + magnetostrictive materials



No substrate clamping to Maximize effect

Graphene transfer



Remote Epitaxy of Magnetostrictive materials



Exfoliation

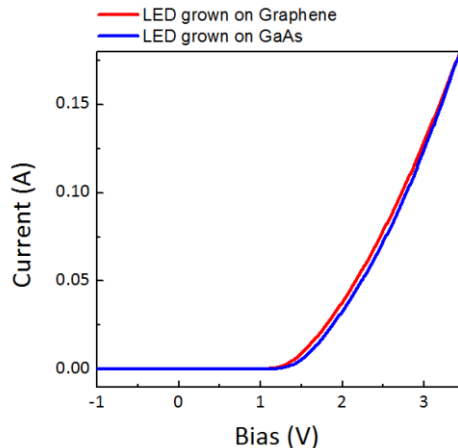


Low-cost flexible LEDs (solid state lighting/microLED)

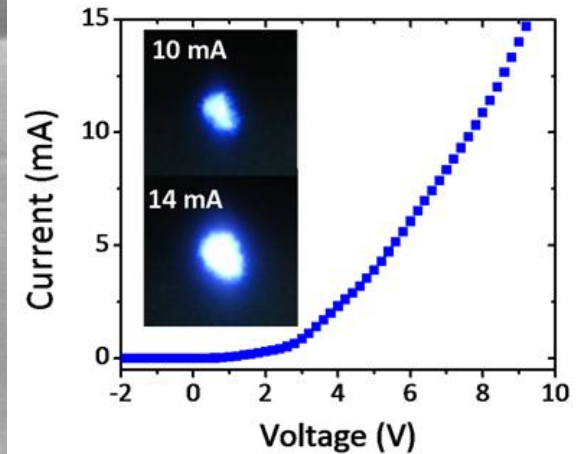
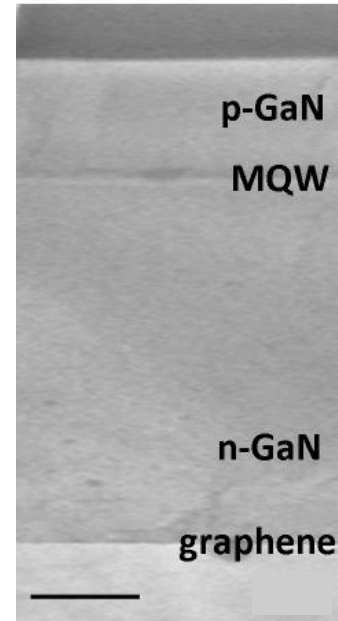
Red LED (III-V)

Dislocation-free
LED on graphene

Light emission from
LEDs on graphene



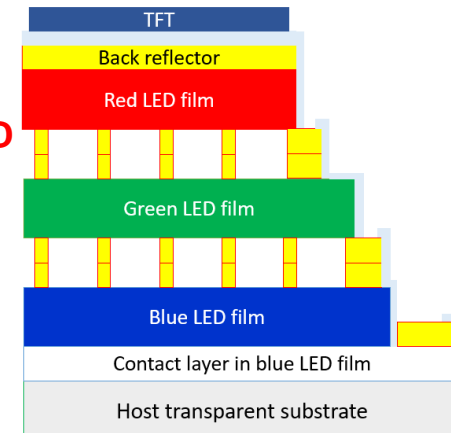
Blue LED (III-N)



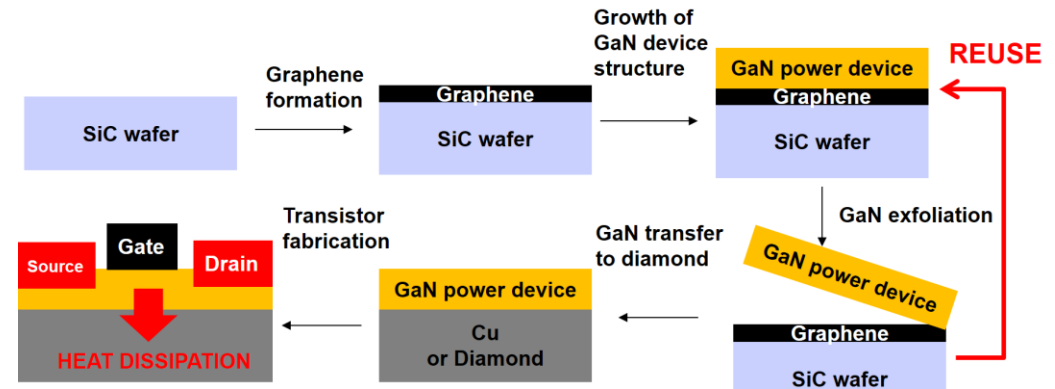
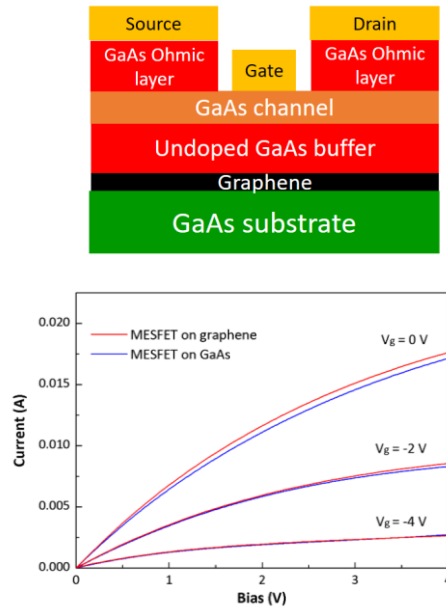
Dislocation-free GaN obtainable
by GaN growth on graphene/GaN

High efficiency lighting

High pixel density microLED



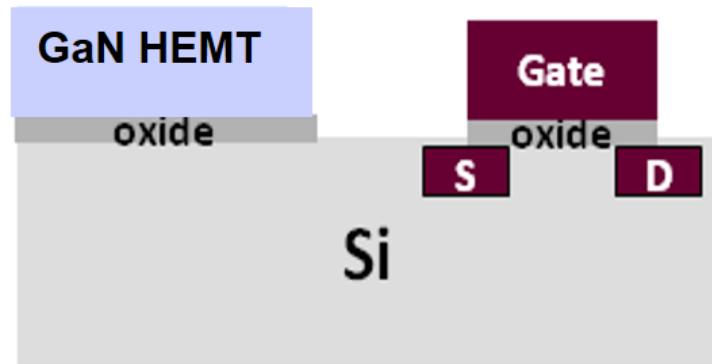
Power electronics



 **LINCOLN LABORATORY**
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Heterointegration

Power transistor



optical interconnect

