Massachusetts Institute of Technology

Extremely cost-effective semiconductor layer-transfer process via graphene & Highly uniform advanced RRAM

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1. 2D material based layer transfer
2. Highly uniform epitaxial RRAM (epiRAM)

1. 2D material based layer transfer (2DLT)

Sponsors

Masdar INSTITUTE

LG

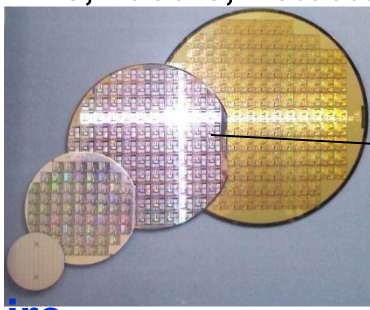
LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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

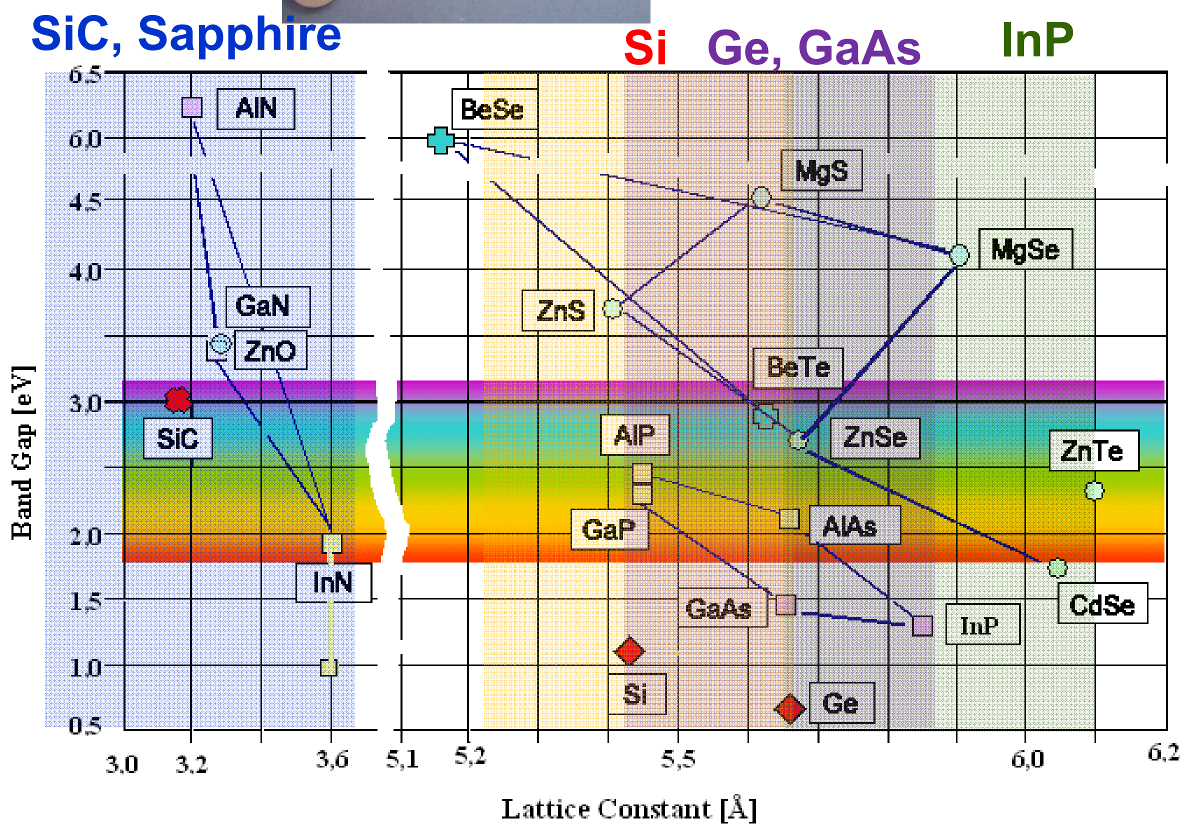
FETs, LEDs, Lasers, Detectors



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

Epitaxial films

Substrate



Price:
SiC > InP > GaAs > Ge >>> Si

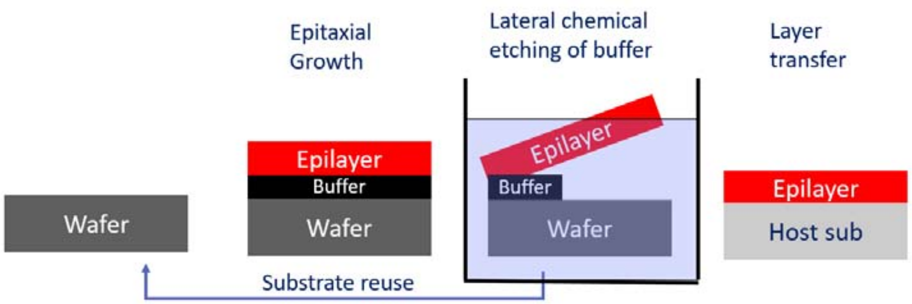
Limited application

Lattice:
InP > GaAs/Ge > Si > SiC

Defect generation

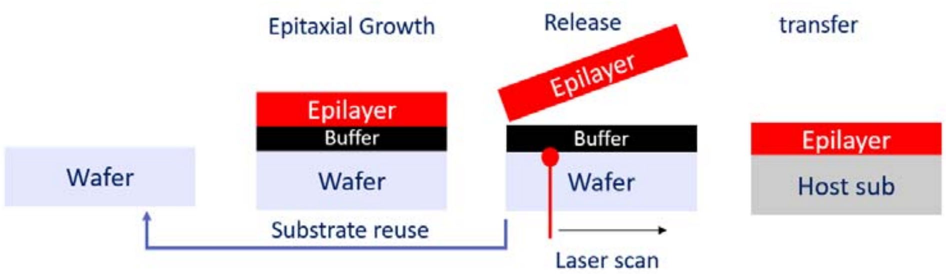
Conventional lift-off technique

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



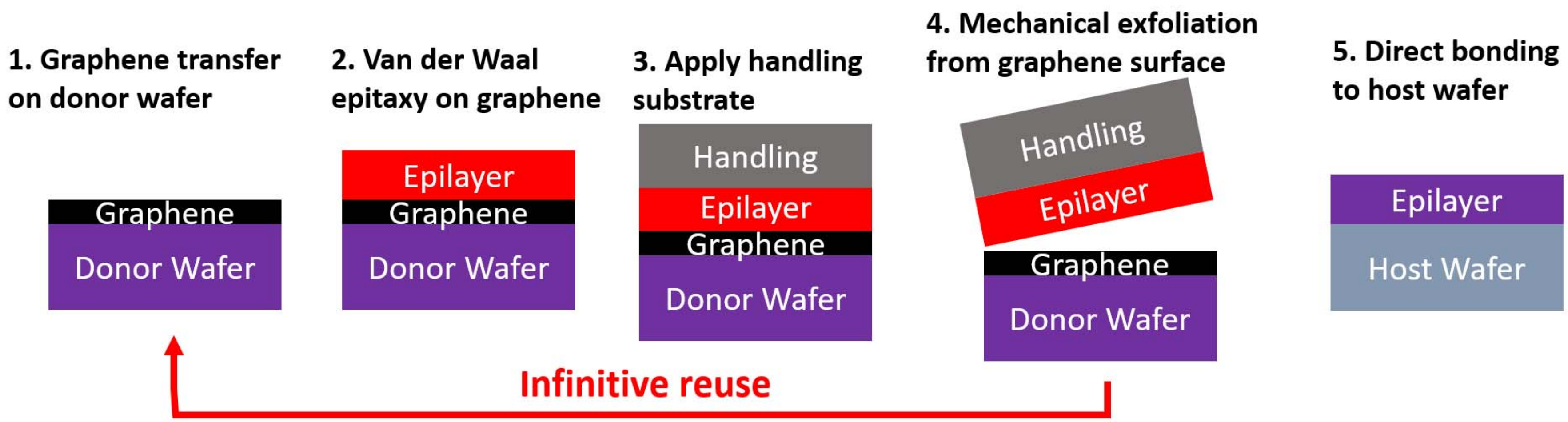
- **Pro: Control of release interface**
- **Cons:**
  - Post-treatment required
  - Slow release
  - Limited application mainly for GaAs & InP

Optical lift-off (Laser lift-off, LLO)



- **Pro: Control of release interface**
- **Cons:**
  - Post-treatment required
  - Cracking from local pressurization
  - Slow release
  - Limited application mainly for transparent substrate

2D material based layer transfer (2DLT)



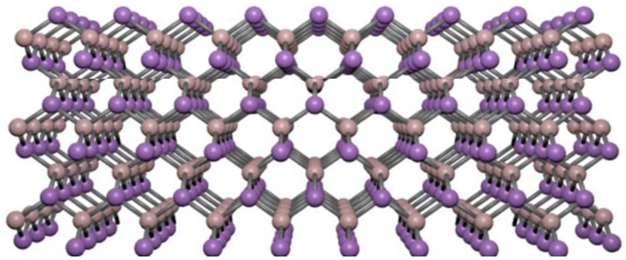
- **sp^2-bonded graphene: No broken bonds on the surface**
  - Precise release from graphene
  - Post-release treatment NOT required
  - **1 sec** release due to weak interaction
  - **Universal for any materials**

2DLT enabled by “REMOTE EPITAXY”

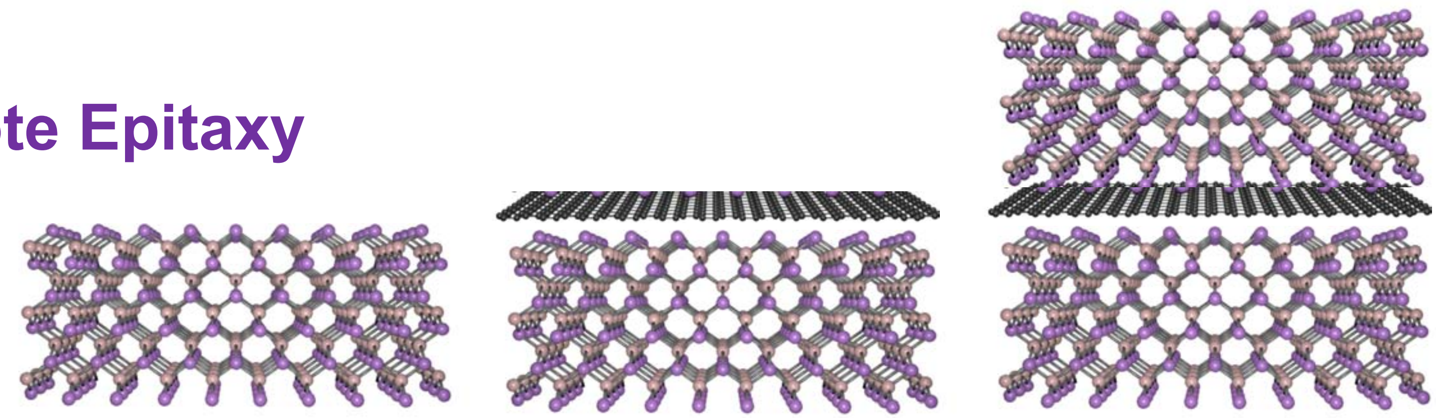
Conventional Epitaxy

Epitaxial Film

Substrate



Remote Epitaxy

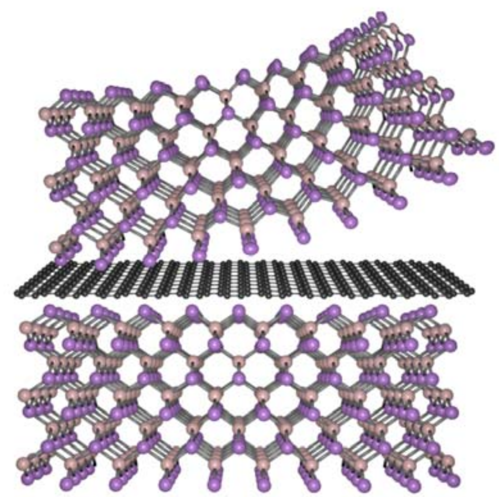


Epitaxial Layer

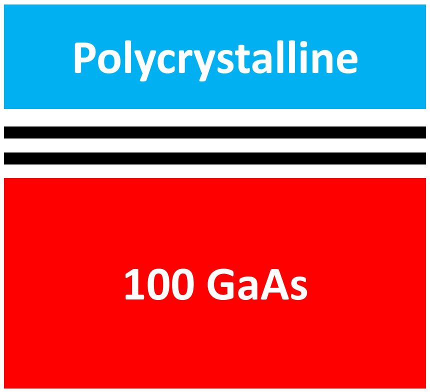
Graphene

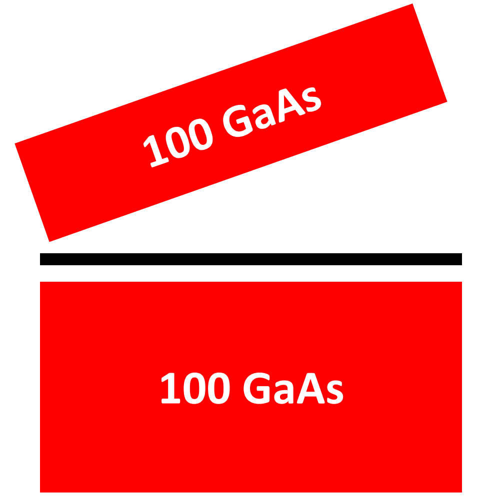
Substrate

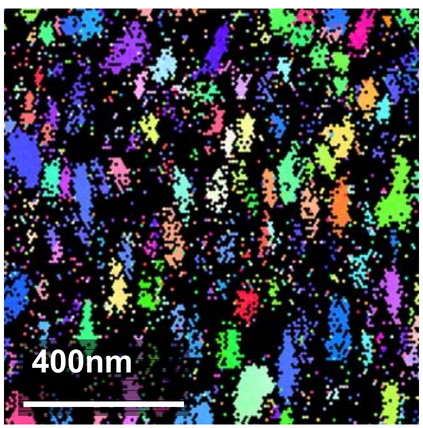
2DLT

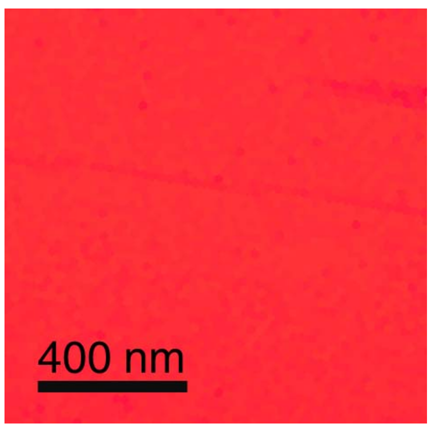


Remote epitaxy of GaAs(001) film on GaAs(001) substrate through “monolayer graphene”

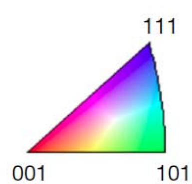


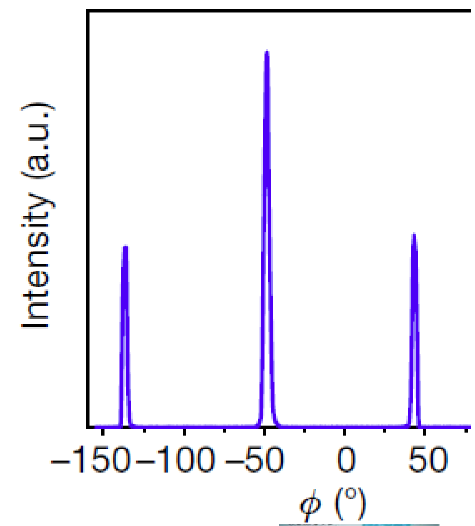






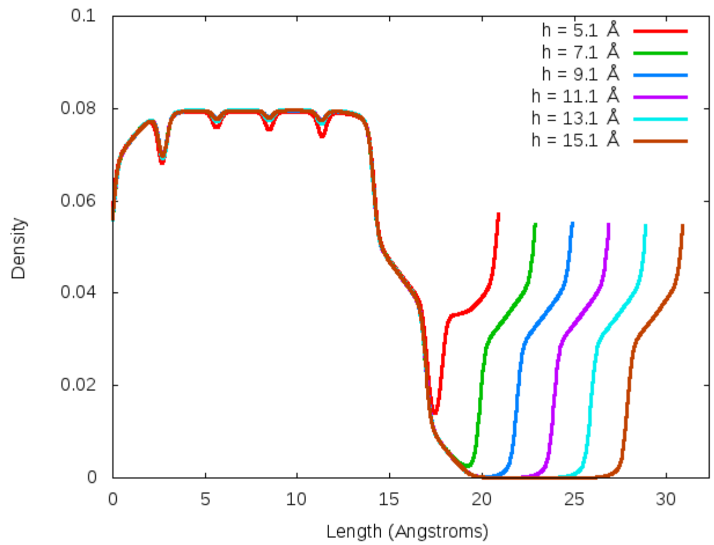
EBSD





Remote homoepitaxy: copy/paste dislocation-free films

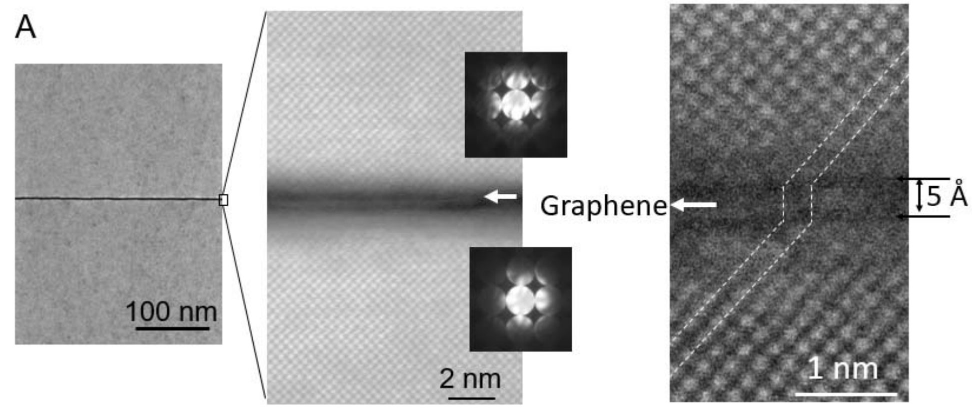
DFT calculation



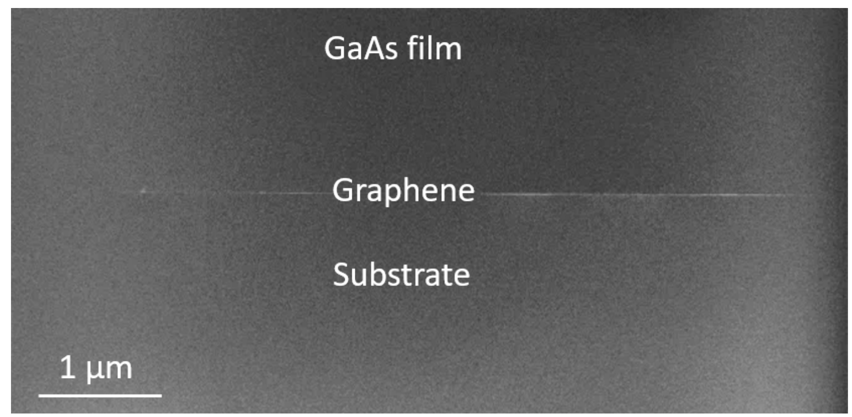
Critical interaction gap: 1 nm

In collaboration with Prof. Kolpak

HRTEM



Dark field XTEM: Strain field



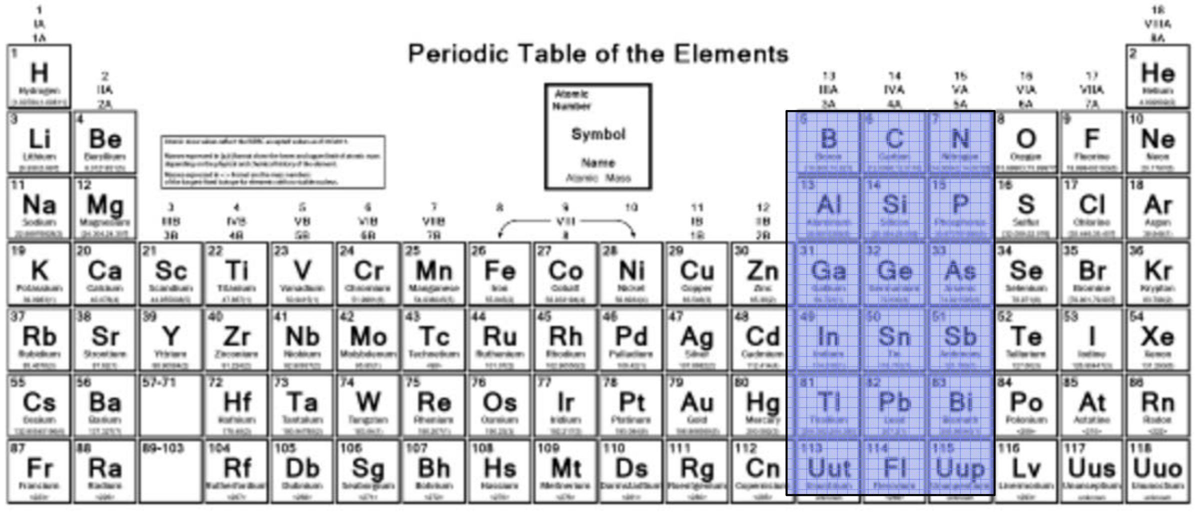
No sign of dislocation

Remote homoepitaxy is possible through graphene

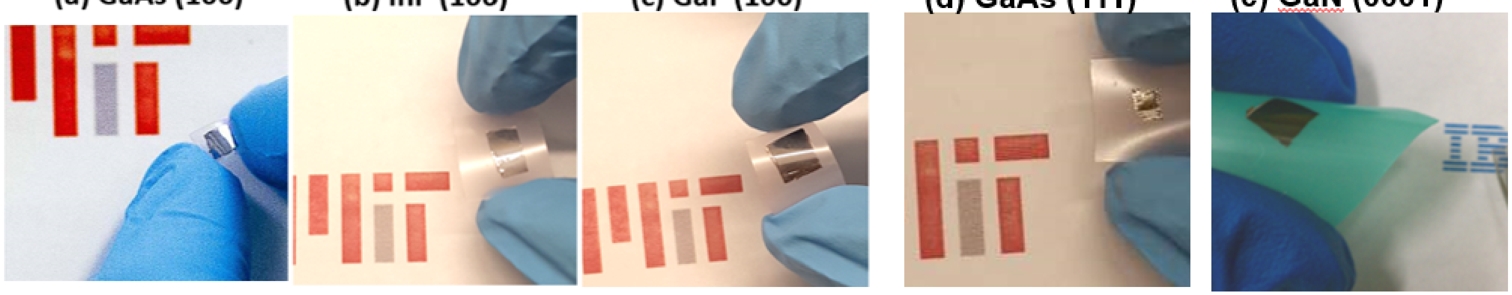
Y. Kim, S. Cruz, J. Kim et al., ***Nature*** (2017)

Unversality of 2DLT

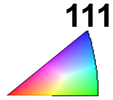
Growth of single-crystalline GaN, GaAs, InP, GaP, Ge on graphene



(a) GaAs (100) (b) InP (100) (c) GaP (100) (d) GaAs (111) (e) GaN (0001)

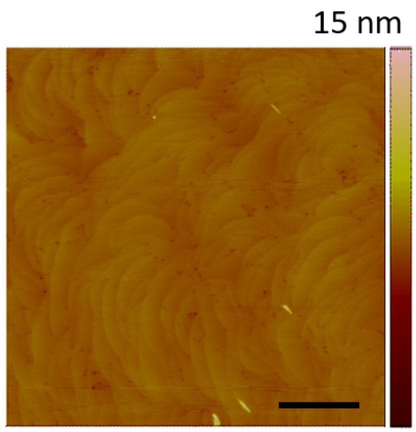


EBSD mapping

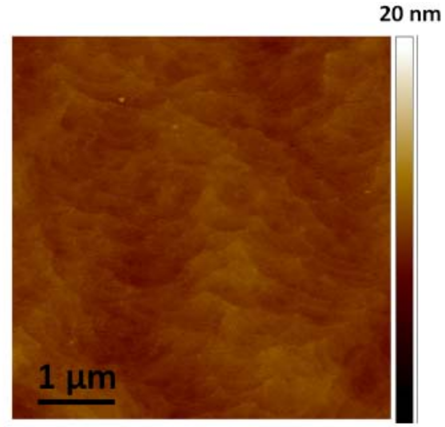


Graphene Reusability (GaN as an example)

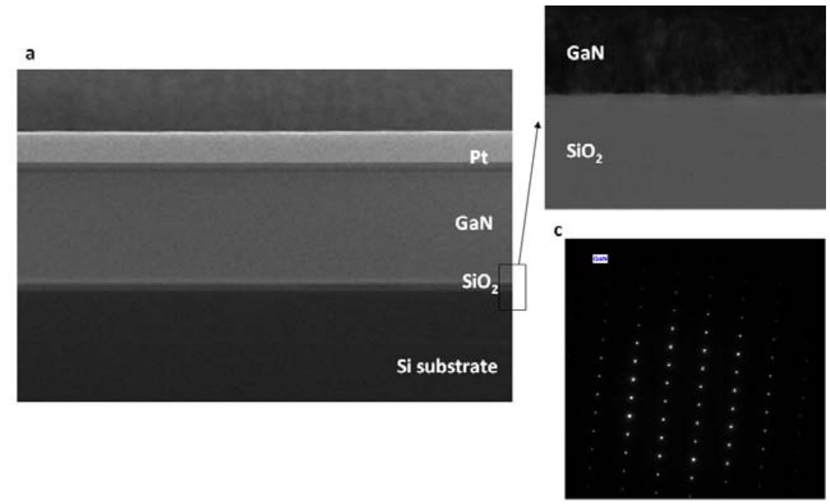
Front Surface
(RMS roughness: 0.3 nm)

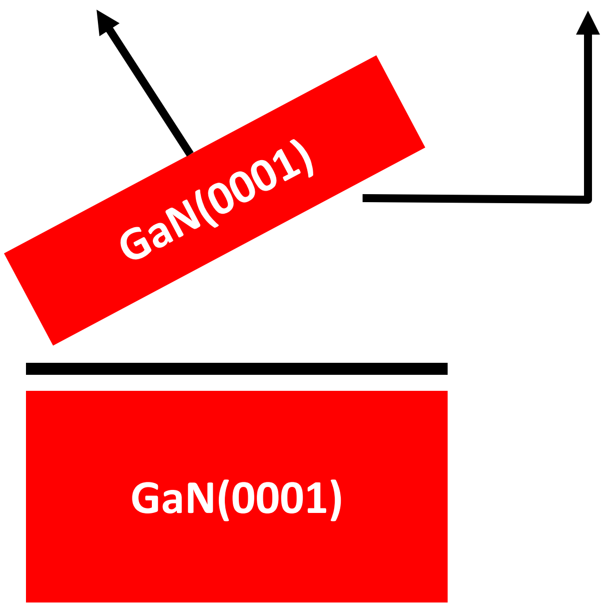


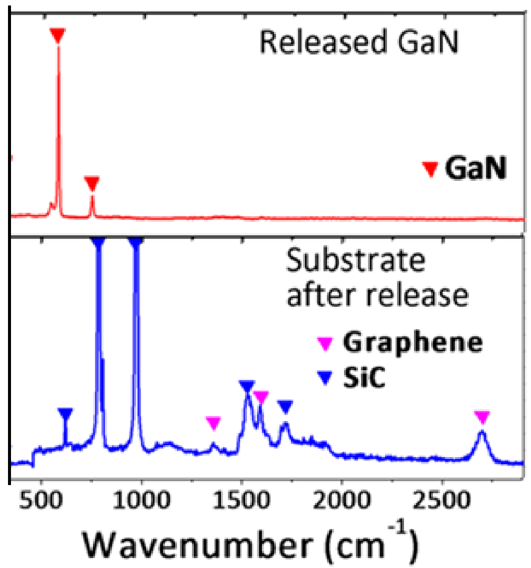
Released Surface
(RMS roughness: 0.3 nm)



Direct bondability







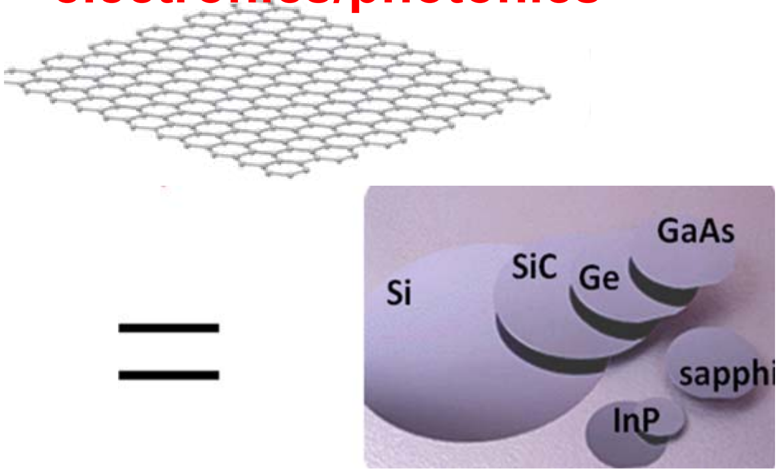
J. Kim et al.,
Nature Communications
Vol. 5, 4836 (2014)

No post-treatment required for further recycle

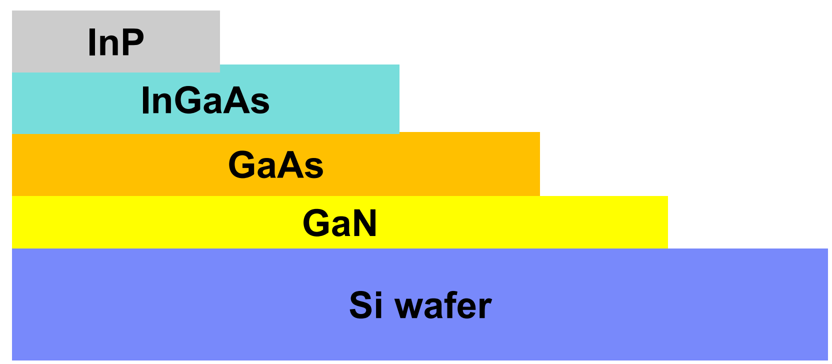
Role of graphene

- Turning wafers into the copy machine
- Dislocation-reducer/filter
- Release layer → 1sec release
- Wafer Surface protection → infinite reuse

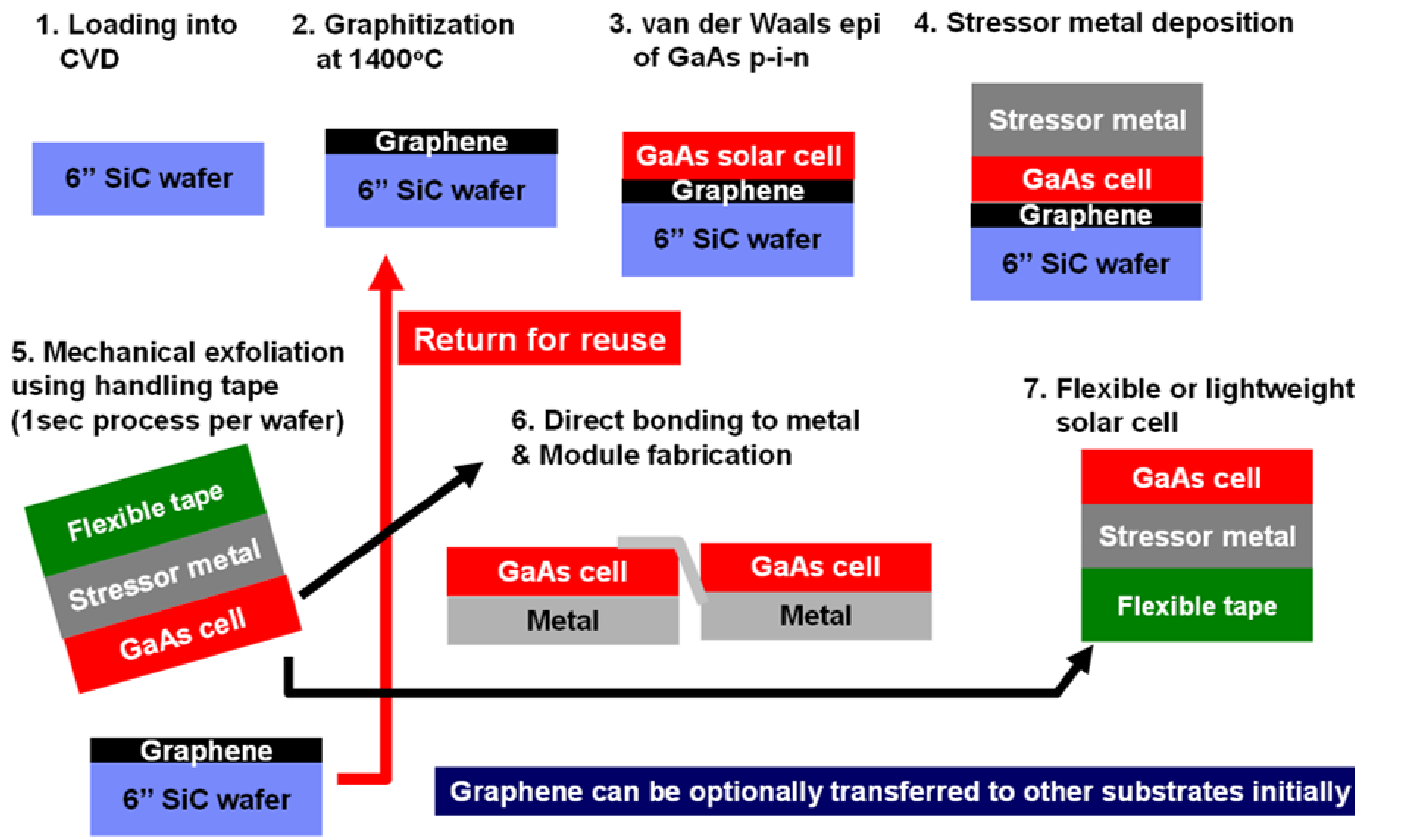
Wide application of non-Si electronics/photonics



Enabled heterointegration

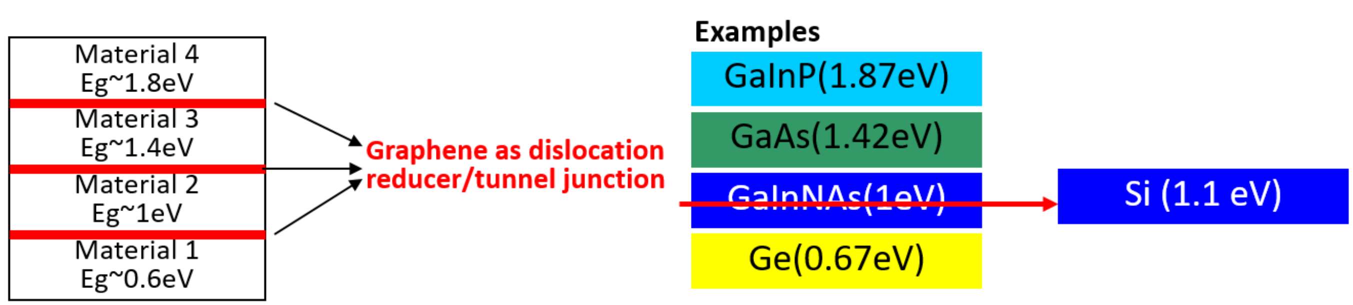


Implication for PV technology



Sponsor: LG

III-V multijunction solar cells for E_g oriented design



Sponsor: Masdar Institute

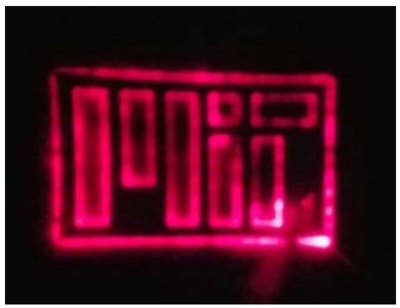
Implication for display/lighting technology

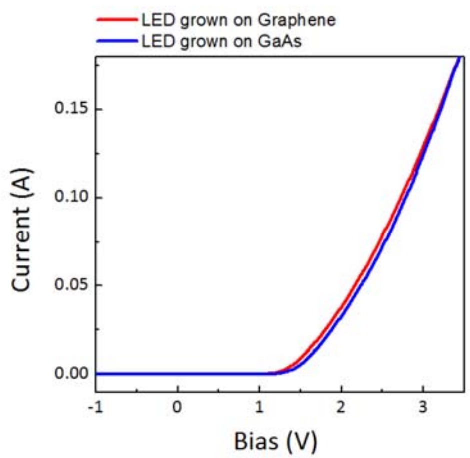
Low-cost flexible LEDs (solid state lighting/microLED)

Red LED (III-V)

Dislocation-free LED on graphene

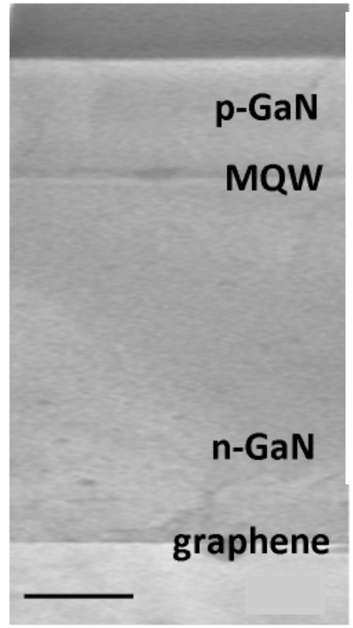
Light emission from LEDs on graphene

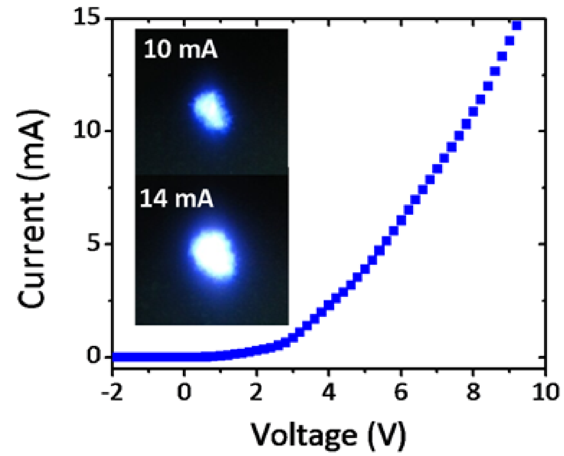




Y. Kim, S. Cruz, J. Kim et al., ***Nature*** (2017)

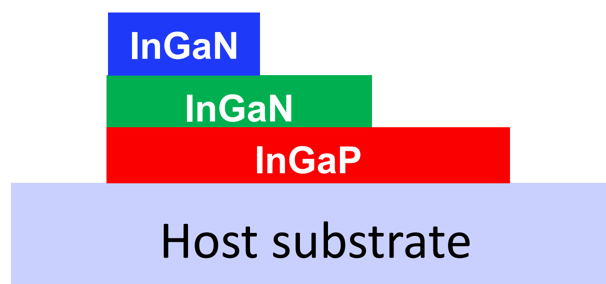
Blue LED (III-N)



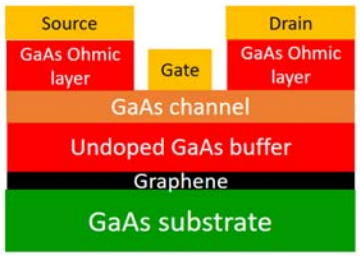


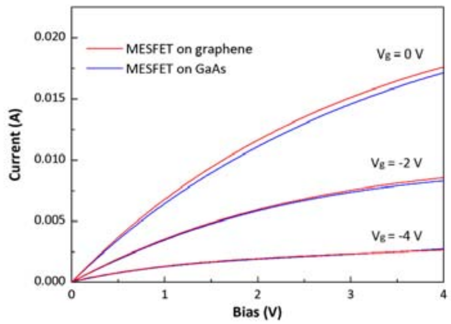
Dislocation-free GaN obtainable by GaN growth on graphene/GaN

High efficiency lighting
High pixel density microLED

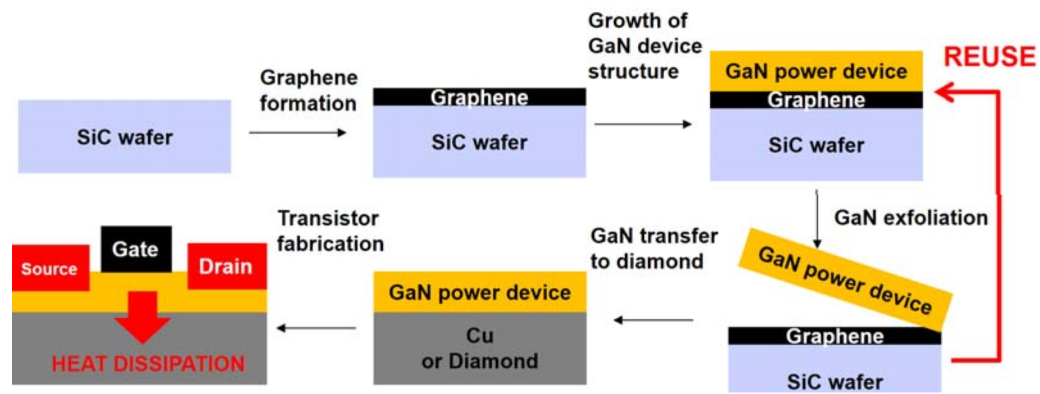


Implication for power electronics/heterointegration





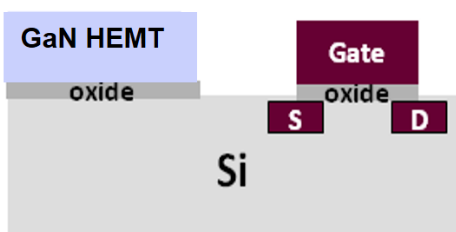
Power electronics



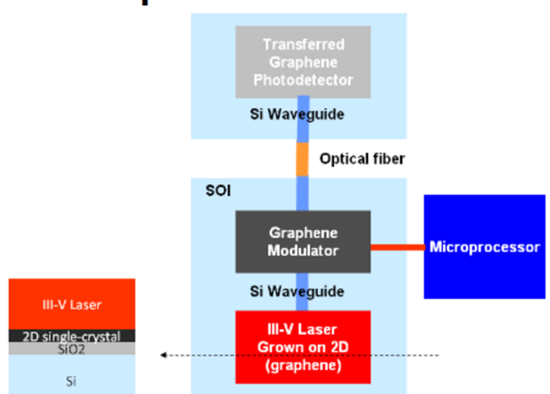
Sponsor: LINCOLN LABORATORY MASSACHUSETTS INSTITUTE OF TECHNOLOGY Thanks to gift from: ANALOG DEVICES

Heterointegration

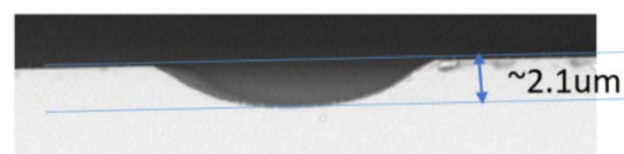
Power transistor



optical interconnect



Wide field of view focal plane arrays

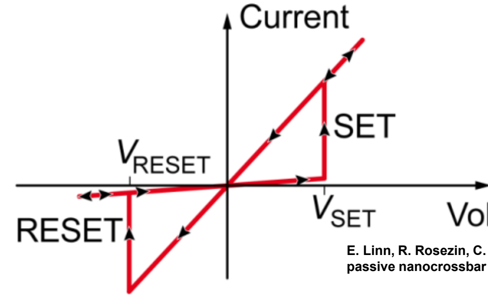


2. Highly uniform advanced RRAM

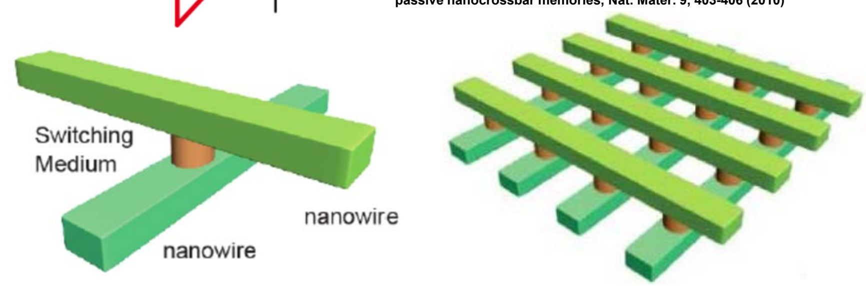
- Epitaxial RAM (epiRAM)

Why Resistive Random Access Memory (RRAM)?

- Wide applications
  - Neuromorphic computing, NVM storage, Logic
- High scalability (10nm size)
- <ns switching
- Large connectivity (2-terminal structure)
- Low energy consumption
- 3D structure
- CMOS compatibility



E. Linn, R. Rosezin, C. Kuegeler, and R. Waser, Complementary resistive switches for passive nanocrossbar memories, Nat. Mater. 9, 403-406 (2010)



S. H. Jo, et al., *Nano lett.*, 9, 2009.

Status

Requirement for commercialization

- High endurance and long retention
- High on-off ratio
- Cycle-to-cycle uniformity
- Device-to-device uniformity
- Current suppression in low voltage/reverse bias → Suppression of sneak paths
- Linear synaptic weight update for neuromorphic (Analog)

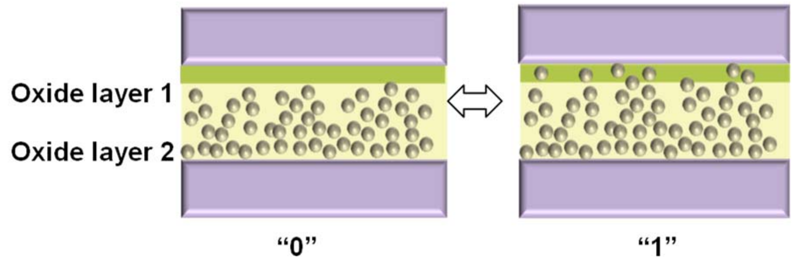
Type	DC on/off ratio (10^n)	Retention	Endurance (10^n cycles)	Set Voltage Spatial Variation (σ/μ)	Set Voltage Temporal Variation (σ/μ)	Reference
a-Si:Ag	4	X	X	0.03	X	4
HfO_x:Ag	10	~ ms@ RT	6	X	X	11
Al_2O_3/TiO_x	4	14 hr@ 77 °C	3	0.11	X	1
PEI/PEDOT:PSS	1	25 hr@ RT	X	X	X	9
Ta_2O_{5-x}/TaO_{2-x}	1	2.8 hr@ 250 °C	12	X	X	13
ZnO	1	0.3 hr@ RT	2	X	0.06	30
TiO_x	1	2.8 hr@ RT	2	0.10	X	31
SiO_2	3	110 hr@ 85°C	X	0.10	X	32

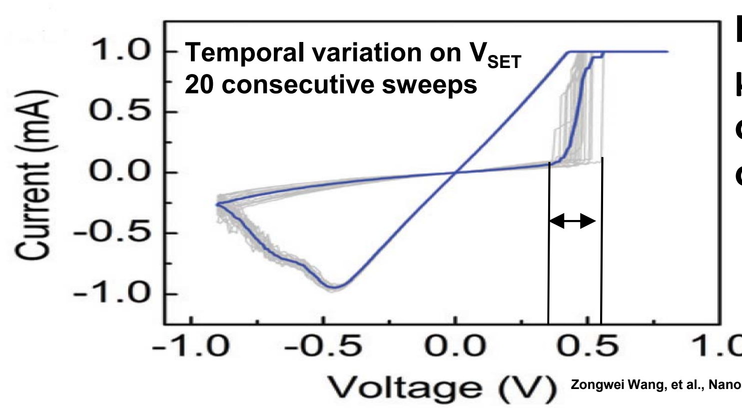
None of the currently reported RRAM fully satisfies requirements

Conventional ReRAM devices- Valence Change Memory (VCM)

- **Good endurance and retention**
- **Device non-uniformity**

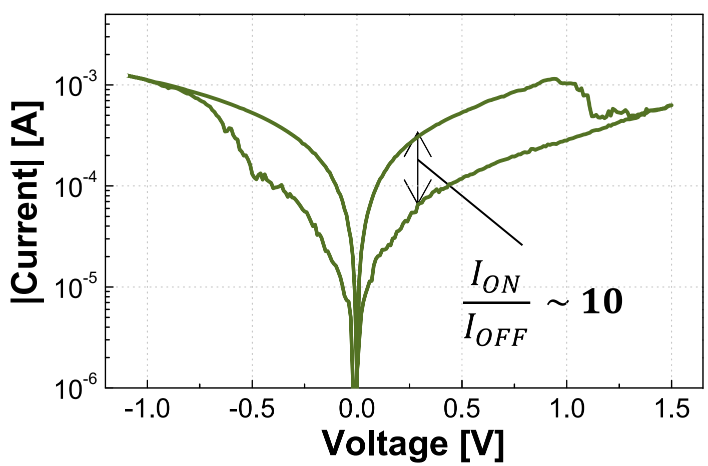
  (Cycle-to-cycle / Device-to-device)
  - Conductive filament is not confined in single path that cause stochastic uncorrelated switching events .
- **Low On-off ratio**
  - Digital: ~10 / Analog: ~2



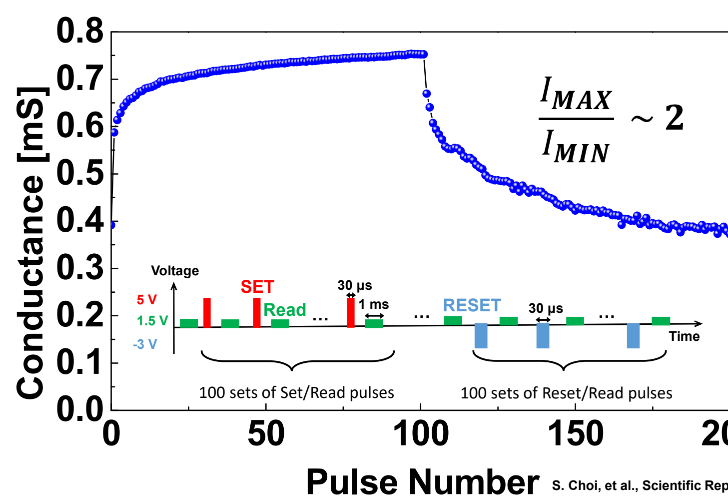


For V_{SET},
μ = 0.45 V
σ =0.05 V
σ/μ = 0.11

Zongwei Wang, et al., Nanoscale, 8, 14015-14022 (2016)

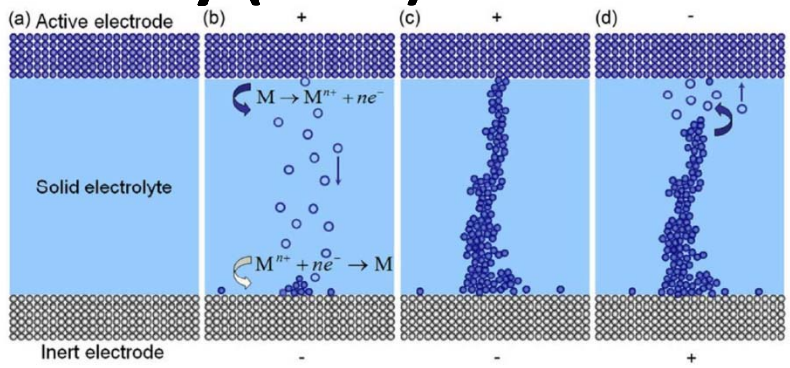


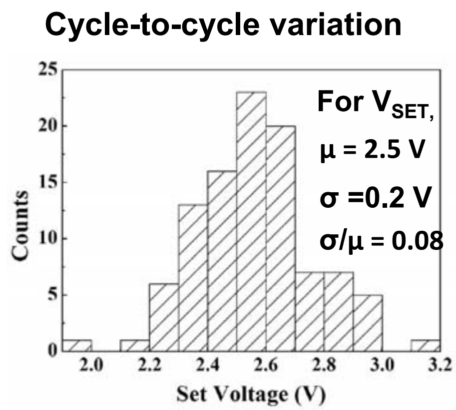
S. Kim, et al., ACS Nano, 8, 10262-10269 (2014)



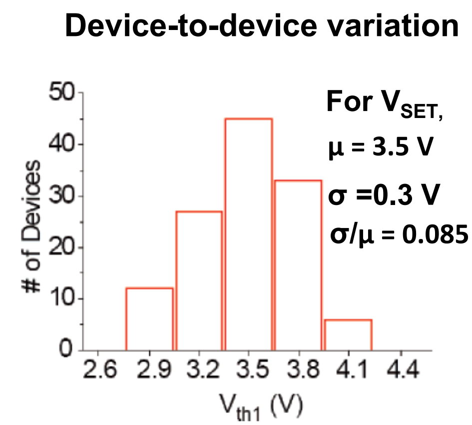
S. Choi, et al., Scientific Reports, 5, (2015)

Conventional ReRAM devices- Electrochemical Metallization Memory (ECM)





S. Gaba, et al., IEEE EDL, 35, 2014



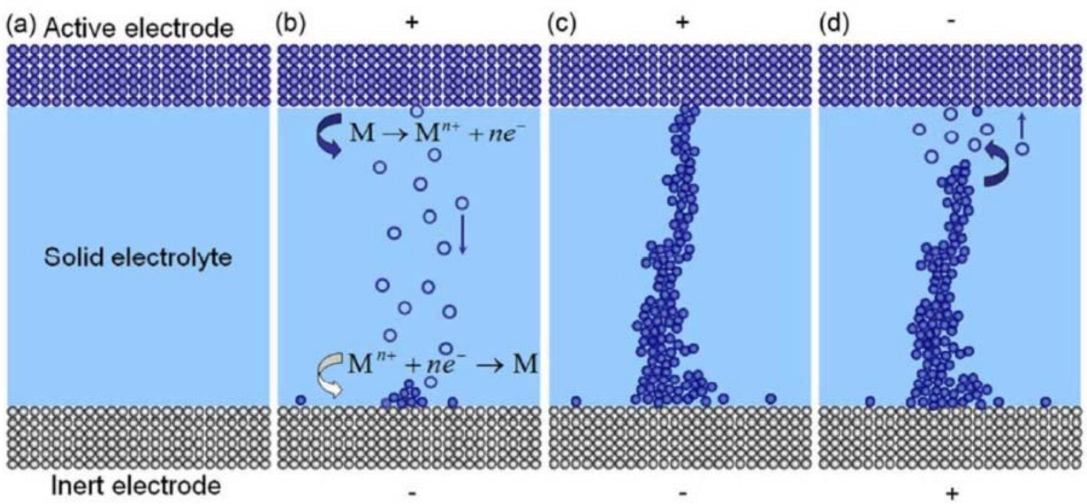
S.H. Jo, et al., Nano Lett., 8, 2008

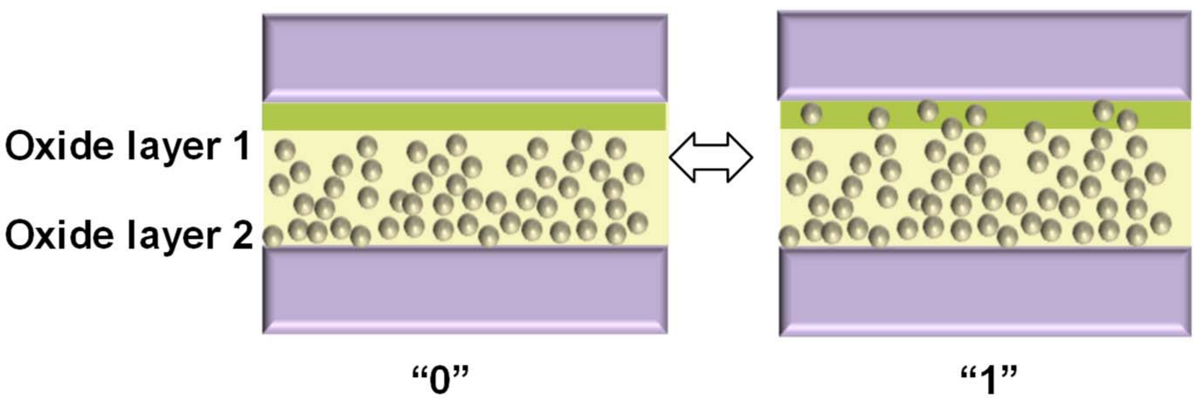
- **High On-off ratio**
  - Digital > 10^4 For reduced power, reduced bit-error-rate(BER) and increased read bandwidth in high density RRAM
- **Device non-uniformity**

  (Cycle-to-cycle / Device-to-device)
- **Retention/Endurance trade-off**
  - Weak Ag-channel formation enhances endurance but reduces retention time
  - Strong Ag-channel formation increases retention time but deteriorate endurance

What is the source of device variation?

- **Due to amorphous switching medium**

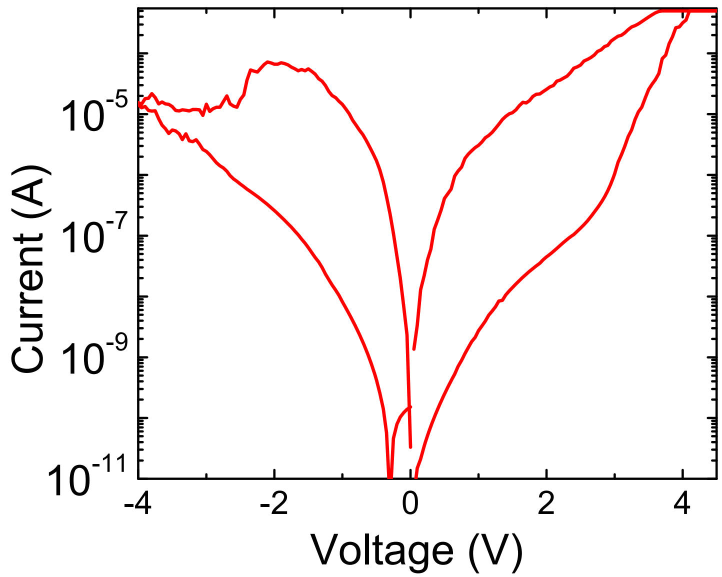




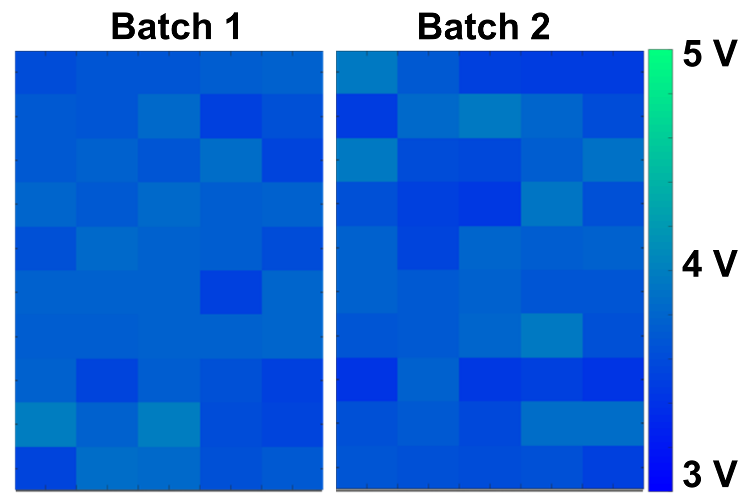
So many filament candidates

Can single-crystalline Si do resistive switching?

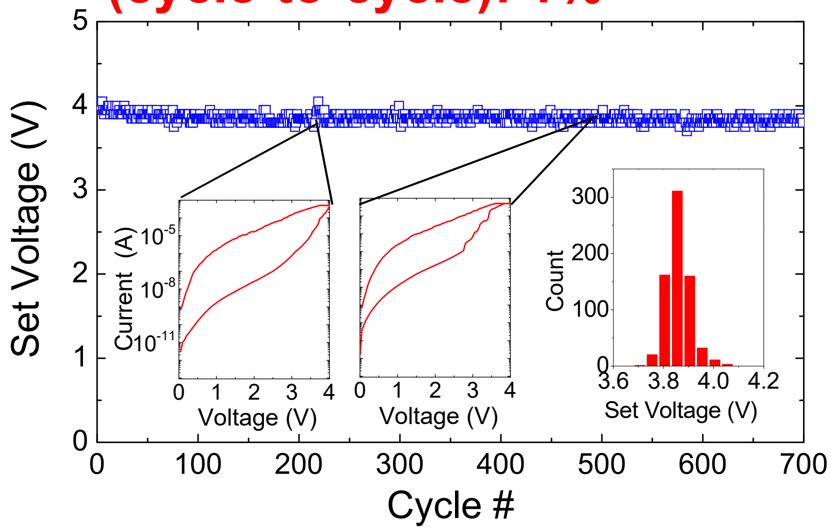
On-off ratio > 10^4

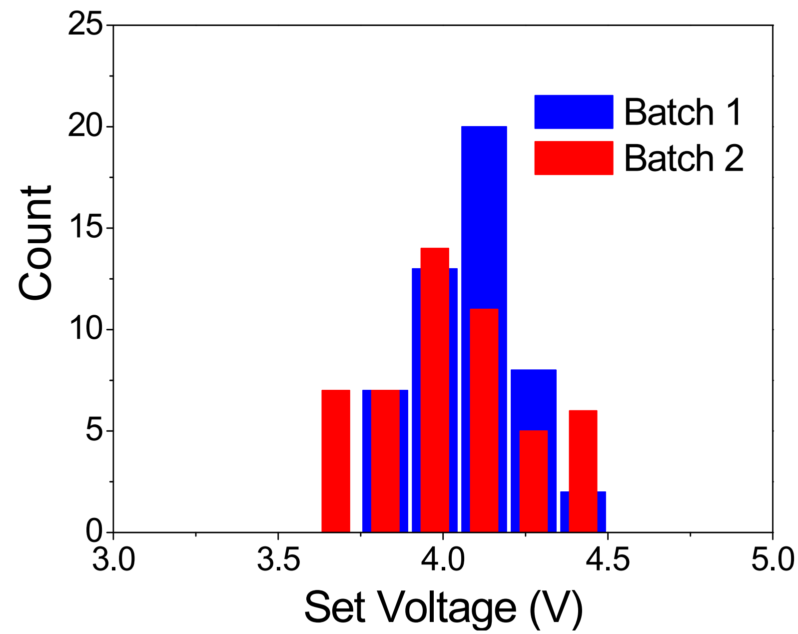


Spatial set V variation (device-to-device): 4%



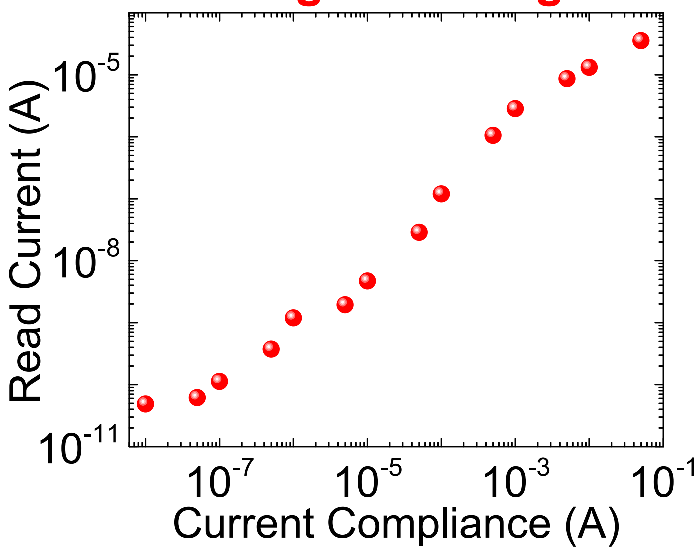
Temporal set V variation (cycle-to-cycle): 1%



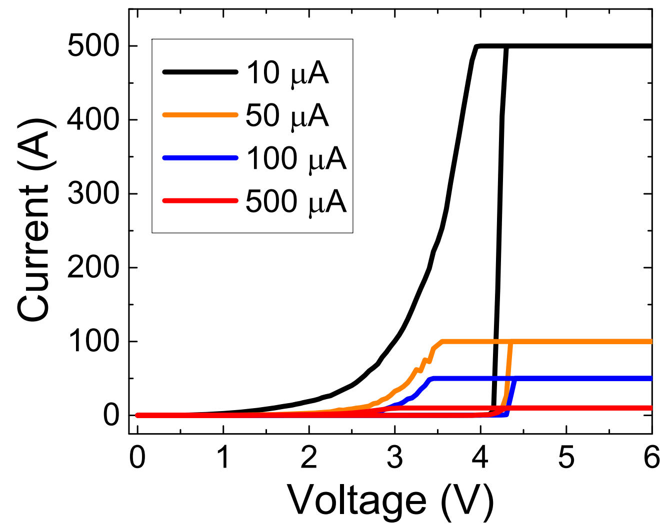


Introduction of epitaxial RAM (epiRAM) for digital

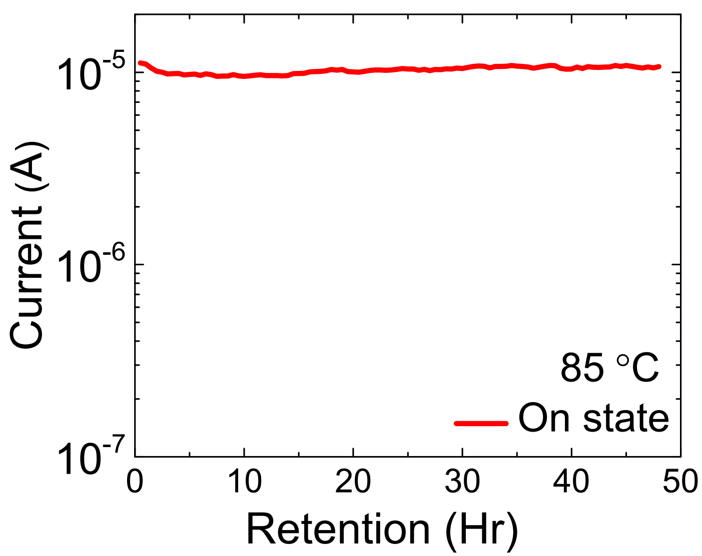
Multilevel storage from self-limiting filament growth



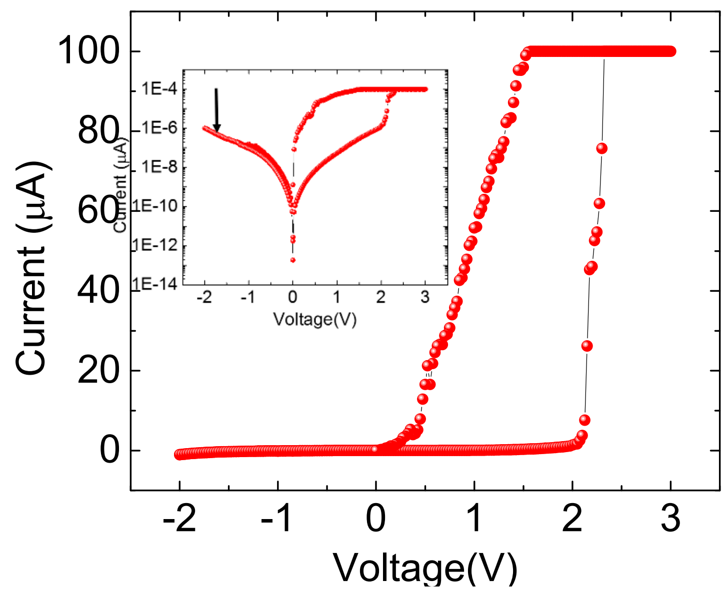
Reliable switching with different c.c



Long retention: Two days at 85°C



Self-selection



Summary of epiRAM performances

New epitaxial RAM (epiRAM) devices contains all required performances for digital and analog applications

- **Long retention with long endurance**
- **Excellent spatial/temporal device uniformity**
- **High on/off ratio**
  - good for both analog and digital
    - Analog: >250, Digital: 10^4
- **Self-selection to reduce the impact of sneak path**
- **Linear weight update**
- **Lower power consumption**

	Retention	Endurance	Retention & Endurance	On-off ratio	Uniformity	Linearity	Self-selection
VCM	Excellent	Excellent	Excellent	Low	Good	Low	N/A
ECM	Excellent	Excellent	Bad	High	Bad	Low	N/A
OURS	**Excellent**	**Excellent**	**Excellent**	**High**	**Excellent**	**High**	**Excellent**

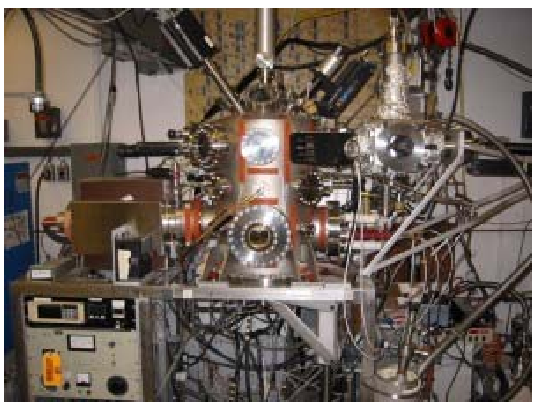
➡ **This will enable large-scale memory arrays for digital application as well as for neuromorphic computing**

Equipment

8" two-chamber MBE system (III-N and III-V)

4" UHV CVD (epitaxial graphene, SiC, Si, Ge, diamond)

2" MBE system (II-VI)



6" MOCVD (III-V, Si, Ge)

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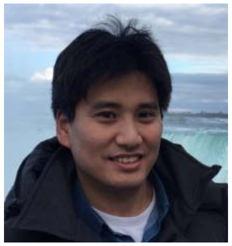

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