



Massachusetts  
Institute of  
Technology

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

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**Research Group**  
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- 1. 2D material based layer transfer**
- 2. Highly uniform epitaxial RRAM (epiRAM)**



Jeehwan Kim  
Research Group

<http://jeehwanlab.mit.edu>



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

Sponsors



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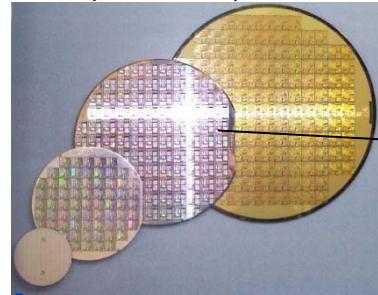
# Major bottleneck for advancing semiconductor technology



**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

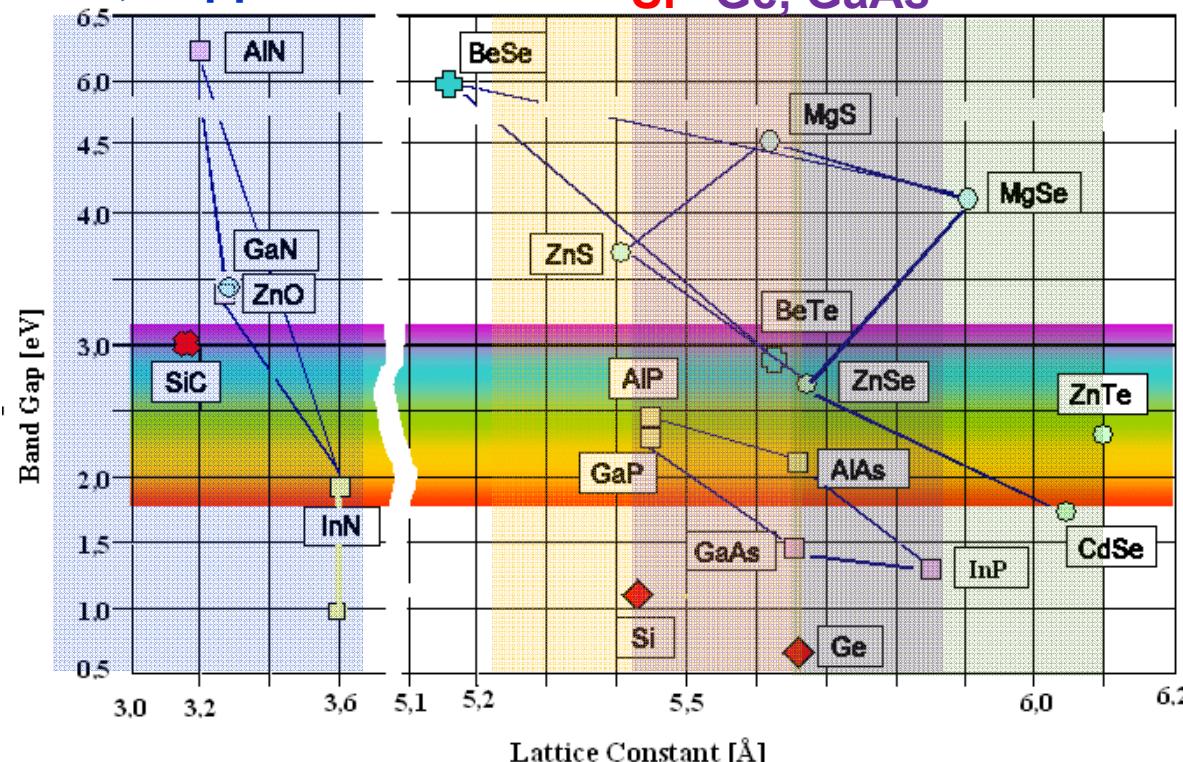
Epitaxial films

Substrate

SiC, Sapphire

Si Ge, GaAs

InP



Price:

SiC > InP > GaAs > Ge >> Si

Limited application

Lattice:

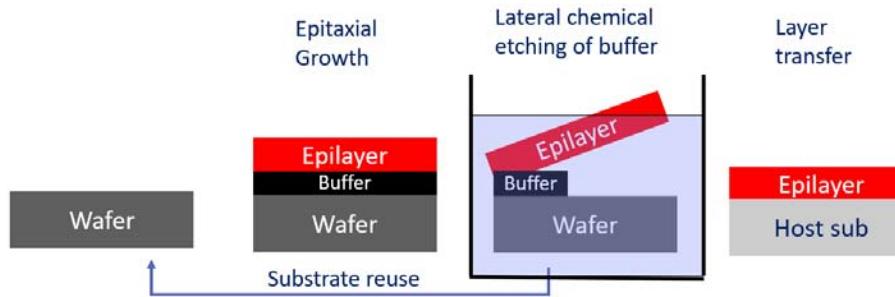
InP > GaAs/Ge > Si > SiC

Defect generation

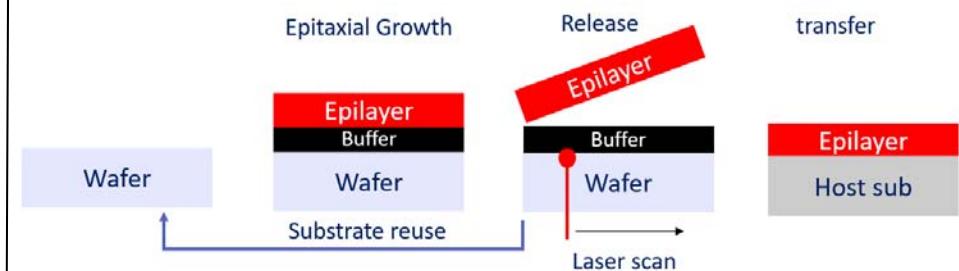
# Conventional lift-off technique



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



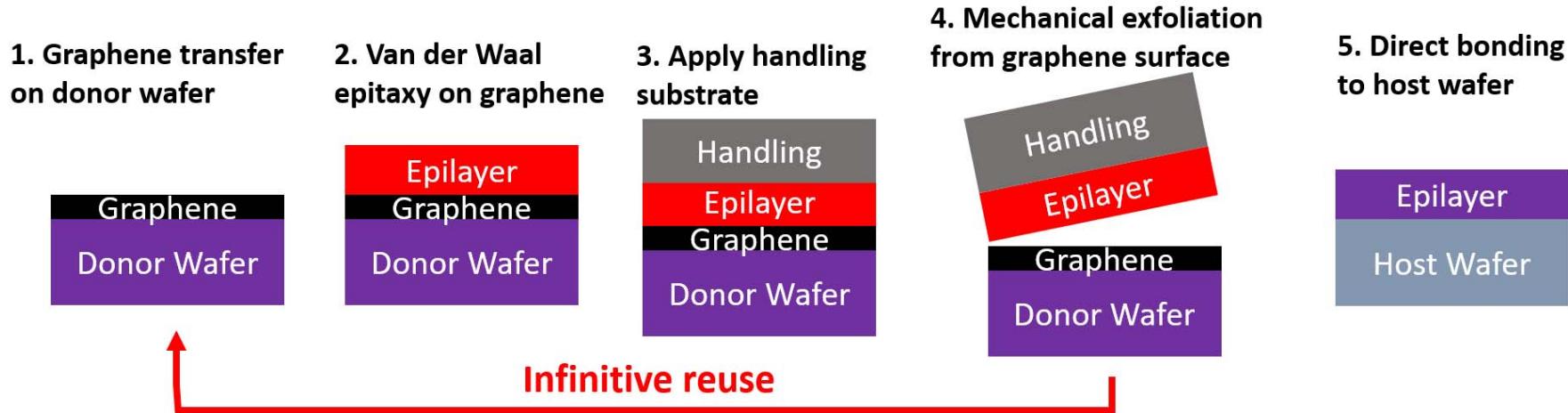
## Optical lift-off (Laser lift-off, LLO)



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

- **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)



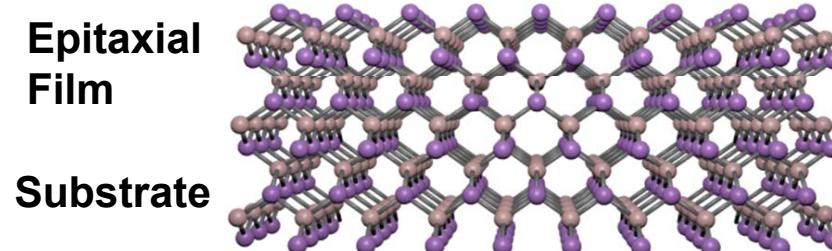
## ■ sp<sup>2</sup>-bonded graphene: No broken bonds on the surface

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

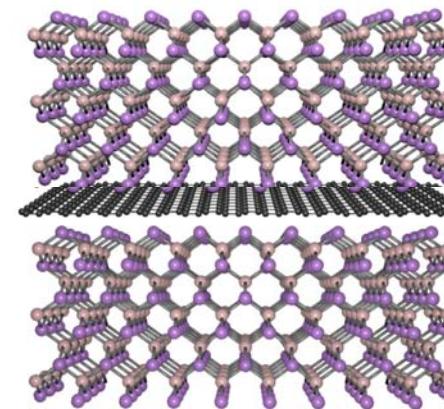
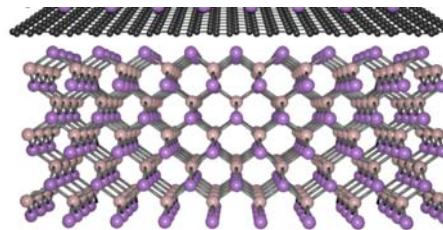
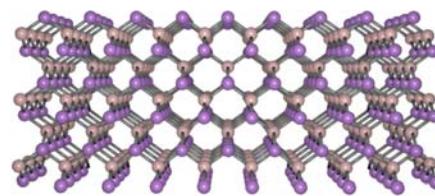
# 2DLT enabled by “REMOTE EPITAXY”



## Conventional Epitaxy

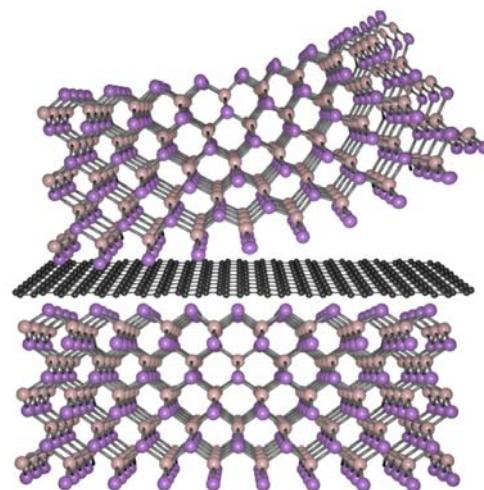


## Remote Epitaxy

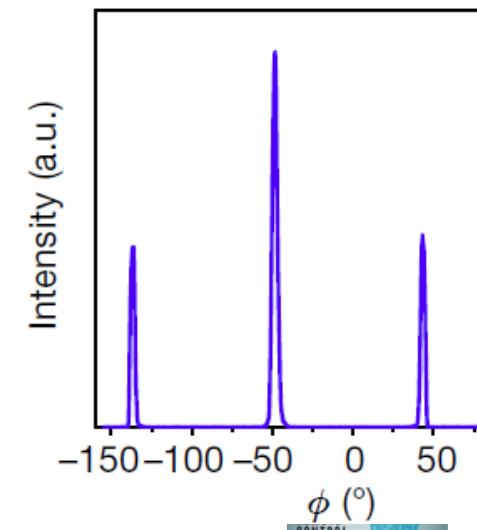
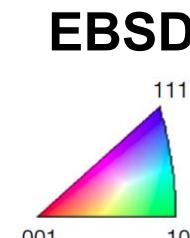
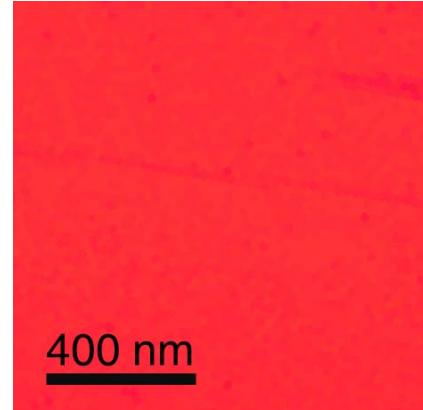
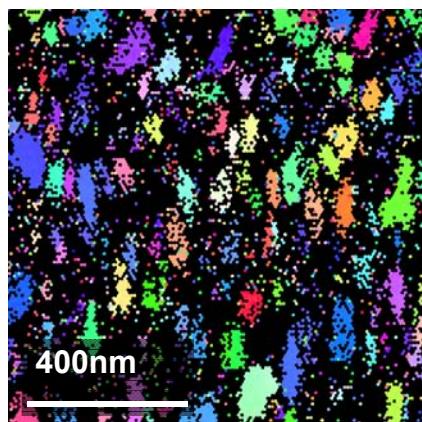
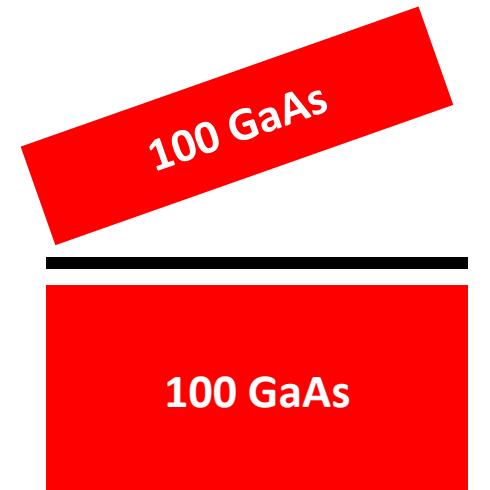
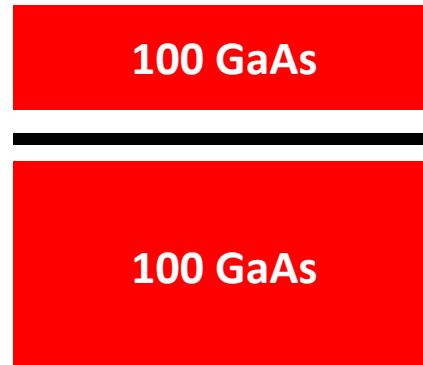
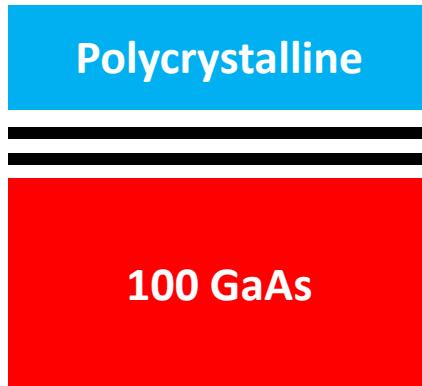


Epitaxial Layer  
Graphene  
Substrate

## 2DLT

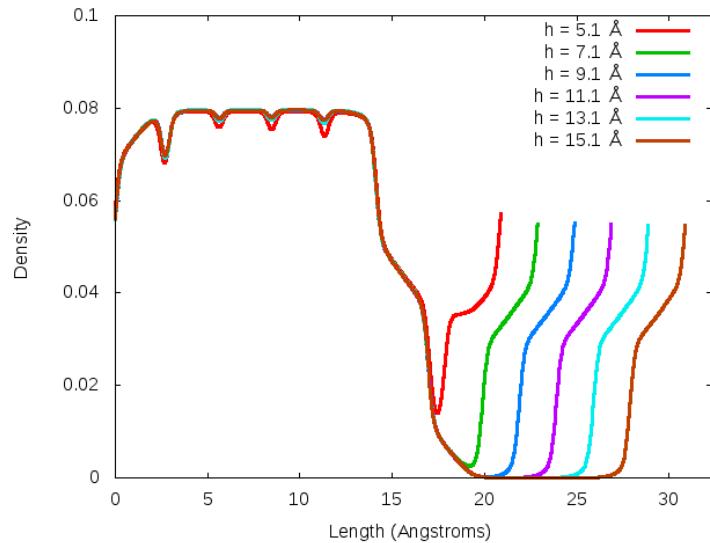


# Remote epitaxy of GaAs(001) film on GaAs(001) substrate through “monolayer graphene”



# Remote homoepitaxy: copy/paste dislocation-free films

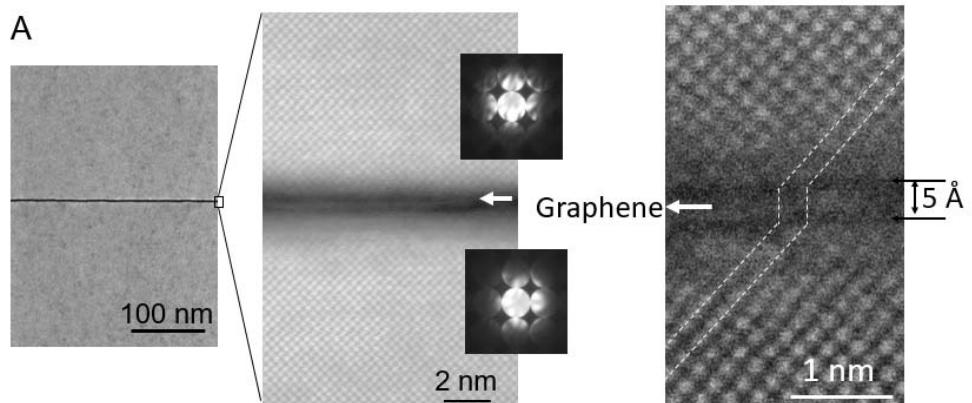
## DFT calculation



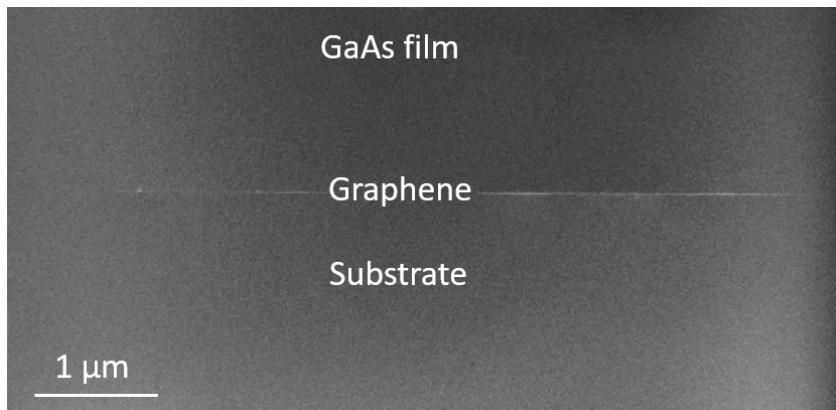
**Critical interaction gap: 1 nm**

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)

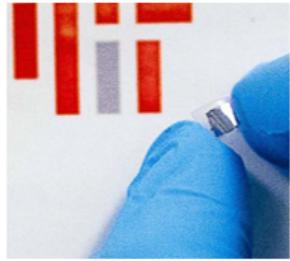
# Universality of 2DLT



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

Periodic Table of the Elements																		
1 IA 1A	H Hydrogen 1st element	2 IA 2A																18 VIIA 8A
3 Li Lithium alkali metal	4 Be Boron alkali earth metal																2 He Helium noble gas	
11 Na Sodium alkali metal	12 Mg Magnesium alkaline earth metal	3 B 3B	4 F <sub>VB</sub> 4B	5 VB	6 VIB 6B	7 VIB 7B	8	9 VIIA 8	10	11 IB 1B	12 IB 2B						16 VIIA 8A	
19 K Potassium alkali metal	20 Ca Calcium alkaline earth metal	21 Sc Scandium transition metal	22 Ti Titanium transition metal	23 V Vanadium transition metal	24 Cr Chromium transition metal	25 Mn Manganese transition metal	26 Fe Iron transition metal	27 Co Cobalt transition metal	28 Ni Nickel transition metal	29 Cu Copper transition metal	30 Zn Zinc transition metal	31 Ga Gallium post-transition metal	32 Ge Germanium post-transition metal	33 As Arsenic post-transition metal	34 Se Selenium post-transition metal	35 Br Bromine halogen	36 Kr Krypton noble gas	
37 Rb Rubidium alkali metal	38 Sr Strontium alkaline earth metal	39 Y Yttrium lanthanide	40 Zr Zirconium transition metal	41 Nb Niobium transition metal	42 Mo Molybdenum transition metal	43 Tc Technetium transition metal	44 Ru Ruthenium transition metal	45 Rh Rhodium transition metal	46 Pd Palladium transition metal	47 Ag Silver transition metal	48 Cd Cadmium transition metal	49 In Indium post-transition metal	50 Sn Tin post-transition metal	51 Sb Antimony post-transition metal	52 Te Tellurium post-transition metal	53 I Iodine halogen	54 Xe Xenon noble gas	
55 Cs Cesium alkali metal	56 Ba Barium alkaline earth metal	57-71 Hf Hafnium transition metal	72 Ta Tantalum transition metal	73 W Tungsten transition metal	75 Re Rhenium transition metal	76 Os Osmium transition metal	77 Ir Iridium transition metal	78 Pt Platinum transition metal	79 Au Gold transition metal	80 Hg Mercury transition metal	81 Tl Thallium post-transition metal	82 Pb Lead post-transition metal	83 Bi Bismuth post-transition metal	84 Po Polonium post-transition metal	85 At Astatine halogen	86 Rn Radium alkaline earth metal		
87 Fr Francium alkali metal	88-103 Ra Radium alkaline earth metal	104 Rf Rutherfordium transition metal	105 Db Dubnium transition metal	106 Sg Singapore transition metal	107 Bh Bohrium transition metal	108 Hs Hassium transition metal	109 Mt Meitnerium transition metal	110 Ds Darmstadtium transition metal	111 Rg Roentgenium transition metal	112 Cn Copernicium transition metal	113 Uut Ununtrium post-transition metal	114 Fl Florium post-transition metal	115 Uup Ununpentium post-transition metal	116 Lv Livermorium post-transition metal	117 Uus Ununseptium post-transition metal	118 Uuo Ununoctium post-transition metal		

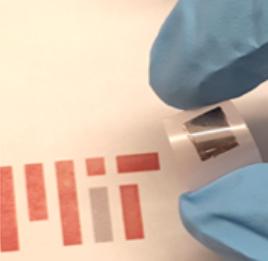
(a) GaAs (100)



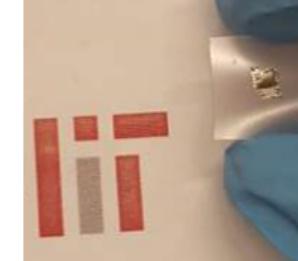
(b) InP (100)



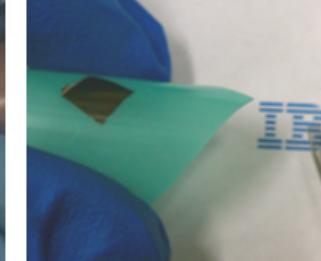
(c) GaP (100)



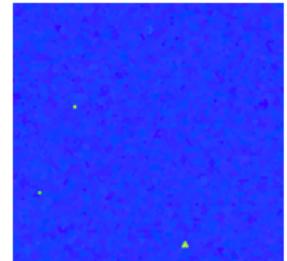
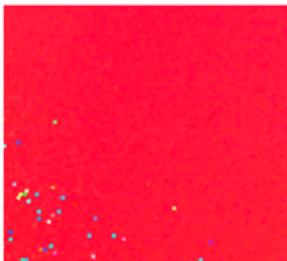
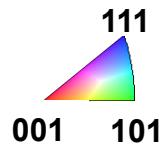
(d) GaAs (111)



(e) GaN (0001)



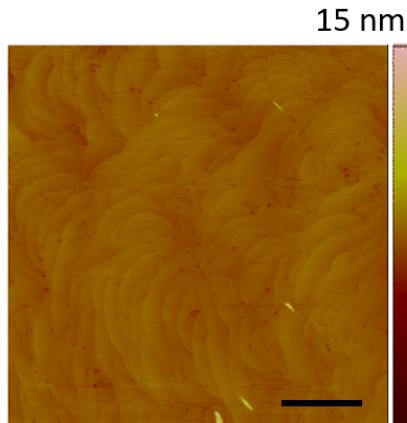
EBSD  
mapping



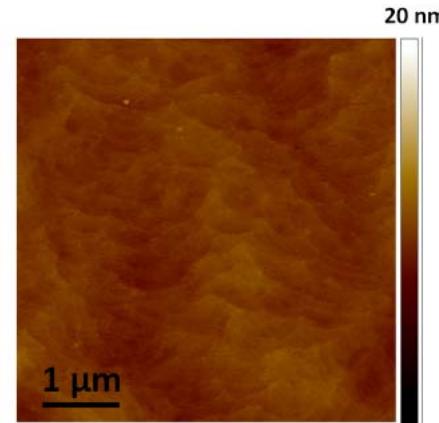
# Graphene Reusability (GaN as an example)



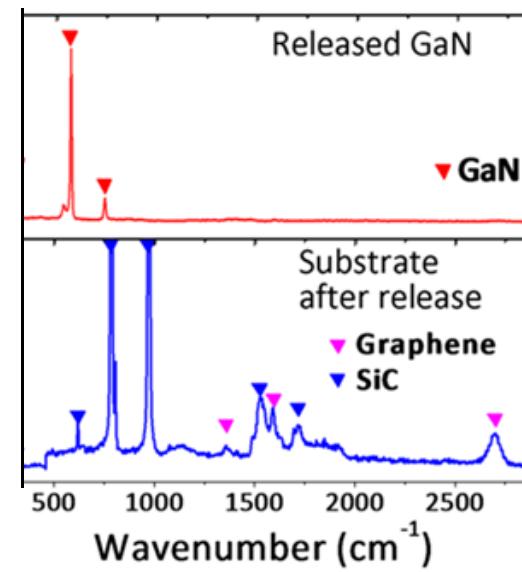
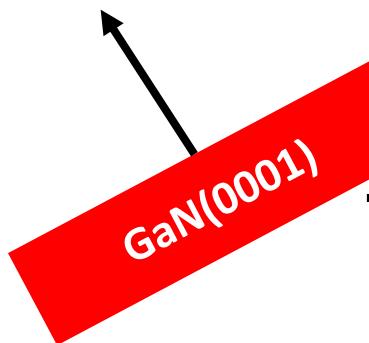
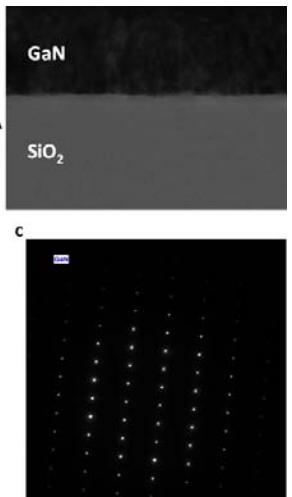
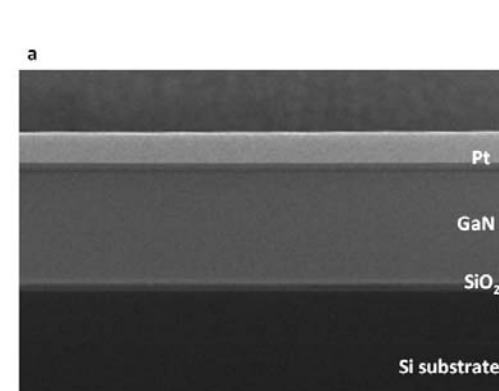
Front Surface  
(RMS roughness: 0.3 nm)



Released Surface  
(RMS roughness: 0.3 nm)



Direct bondability

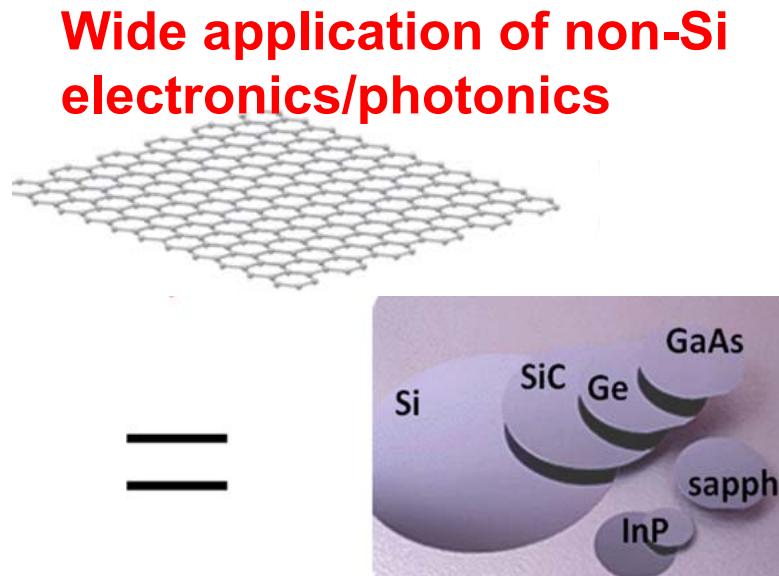


J. Kim et al.,  
*Nature Communications*  
Vol. 5, 4836 (2014)

No post-treatment required for further recycle

# Role of graphene

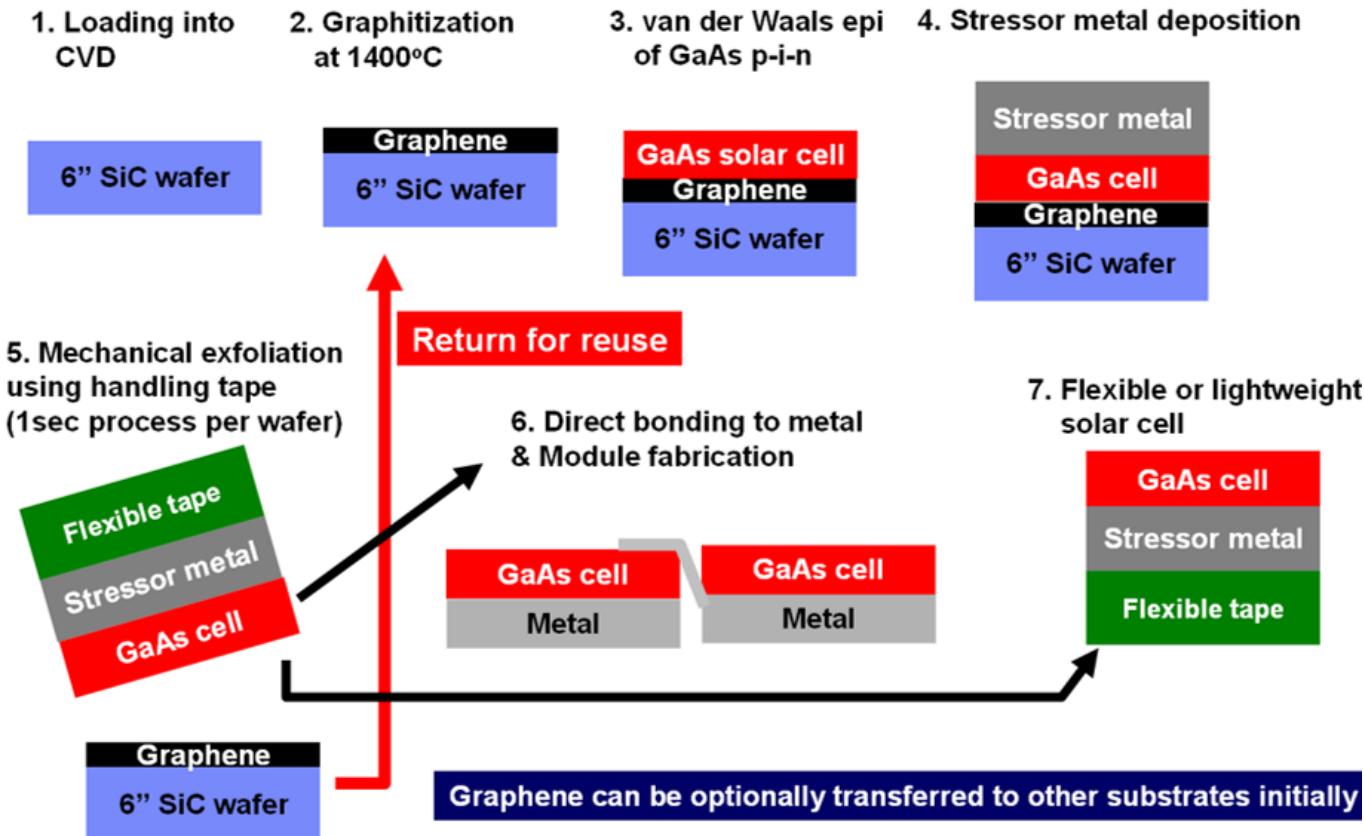
- Turning wafers into the copy machine
- Dislocation-reducer/filter
- Release layer → 1sec release
- Wafer Surface protection → infinite reuse



Enabled heterointegration



# Implication for PV technology

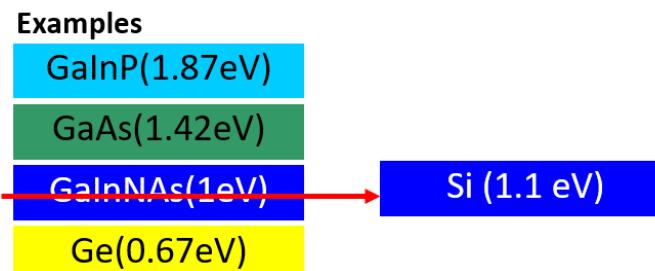


Sponsor: LG

## III-V multijunction solar cells for $E_g$ oriented design

Material 4	$E_g \sim 1.8\text{eV}$
Material 3	$E_g \sim 1.4\text{eV}$
Material 2	$E_g \sim 1\text{eV}$
Material 1	$E_g \sim 0.6\text{eV}$

Graphene as dislocation reducer/tunnel junction



Sponsor: Masdar INSTITUTE

# Implication for display/lighting technology



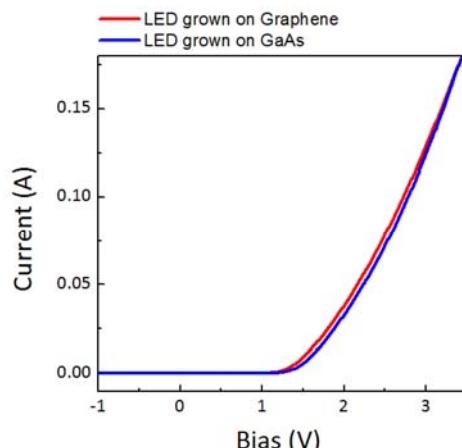
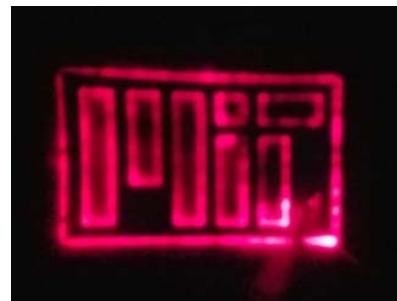
## Low-cost flexible LEDs (solid state lighting/microLED)

### Red LED (III-V)

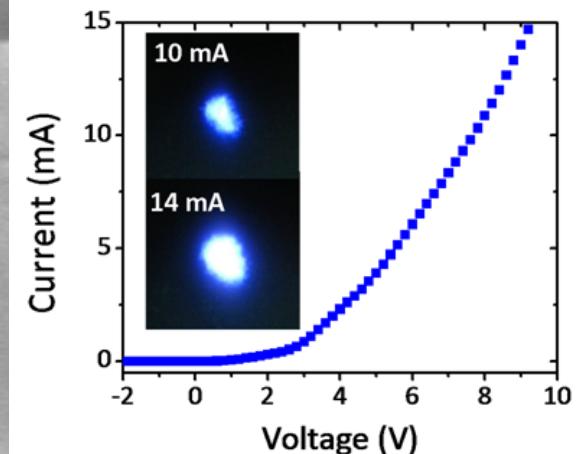
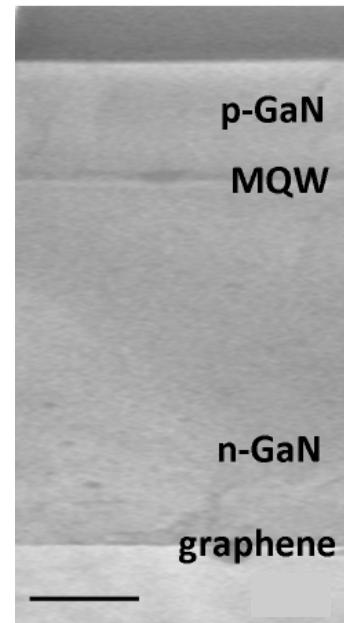
Dislocation-free  
LED on graphene



Light emission from  
LEDs on graphene

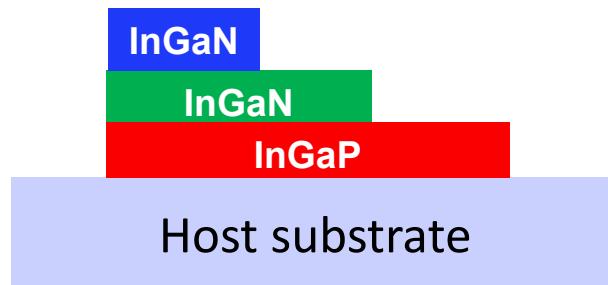


### Blue LED (III-N)

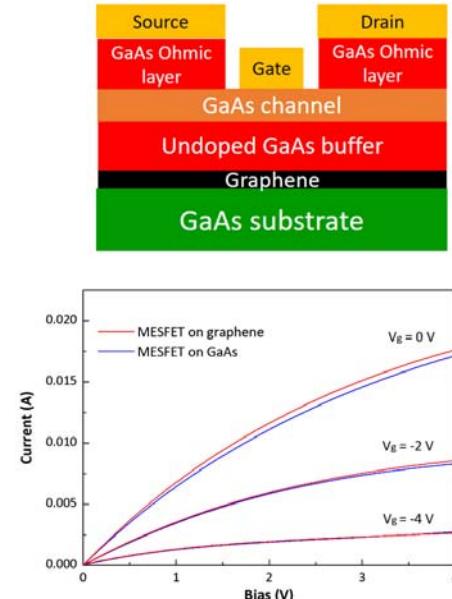


Dislocation-free GaN obtainable  
by GaN growth on graphene/GaN

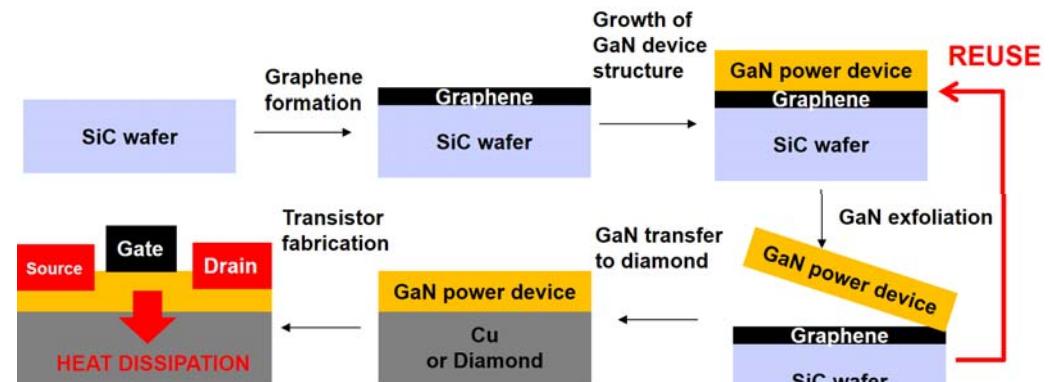
High efficiency lighting  
High pixel density microLED



# Implication for power electronics/heterointegration



## Power electronics



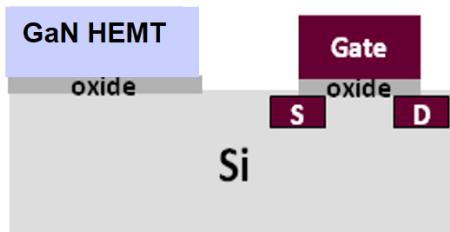
Sponsor: LINCOLN LABORATORY  
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Thanks to gift from:

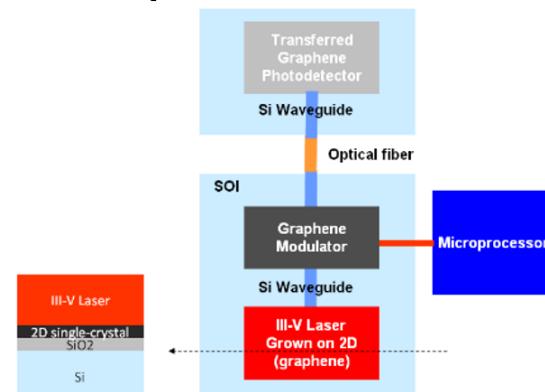
ANALOG  
DEVICES

## Heterointegration

### Power transistor



### optical interconnect



### Wide field of view focal plane arrays





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## 2. Highly uniform advanced RRAM

- Epitaxial RAM (epiRAM)

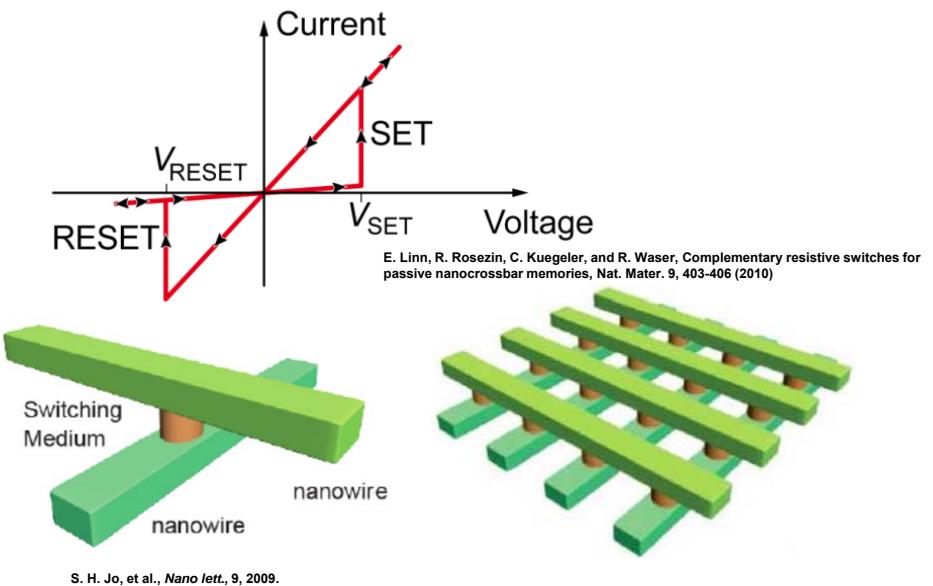


Jeehwan Kim  
Research Group

<http://jeehwanlab.mit.edu>

# 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



## Requirement for commercialization

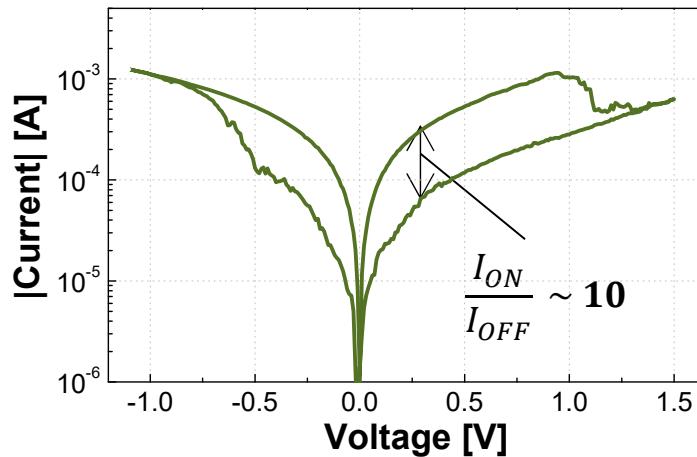
- ❑ High endurance and long retention
- ❑ High on-off ratio
- ❑ Cycle-to-cycle uniformity
- ❑ Device-to-device uniformity
- ❑ Current suppression in low voltage/reverse bias → Suppression of sneak paths
- ❑ Linear synaptic weight update for neuromorphic (Analog)

Type	DC on/off ratio ( $10^n$ )	Retention	Endurance ( $10^n$ cycles)	Set Voltage Spatial Variation ( $\sigma/\mu$ )	Set Voltage Temporal Variation ( $\sigma/\mu$ )	Reference
a-Si:Ag	4	X	X	0.03	X	4
HfO <sub>x</sub> :Ag	10	~ ms@ RT	6	X	X	11
Al <sub>2</sub> O <sub>3</sub> /TiO <sub>x</sub>	4	14 hr@ 77 °C	3	0.11	X	1
PEI/PEDOT:PSS	1	25 hr@ RT	X	X	X	9
Ta <sub>2</sub> O <sub>5-x</sub> /TaO <sub>2-x</sub>	1	2.8 hr@ 250 °C	12	X	X	13
ZnO	1	0.3 hr@ RT	2	X	0.06	30
TiO <sub>x</sub>	1	2.8 hr@ RT	2	0.10	X	31
SiO <sub>2</sub>	3	110 hr@ 85°C	X	0.10	X	32

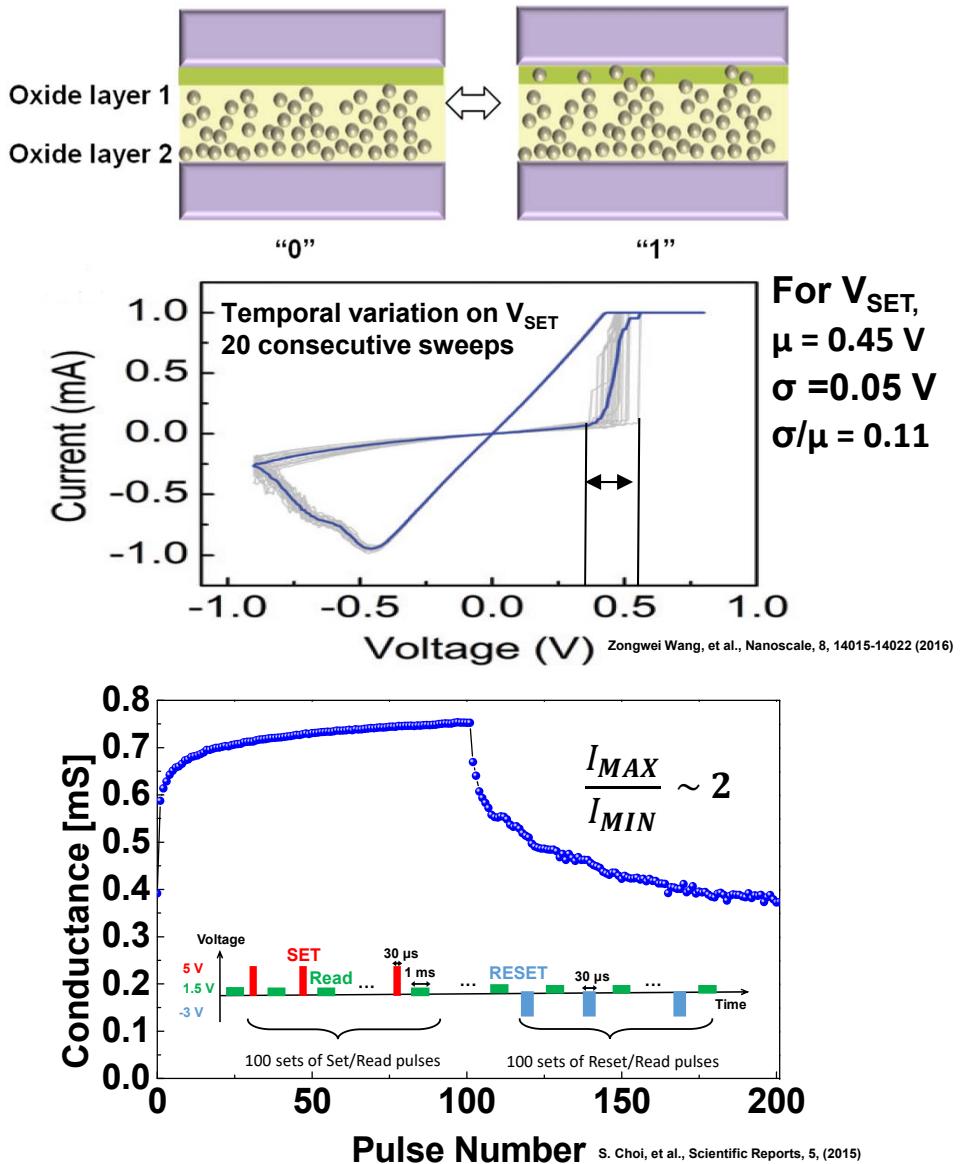
None of the currently reported RRAM fully satisfies requirements

# Conventional ReRAM devices- Valence Change Memory (VCM)

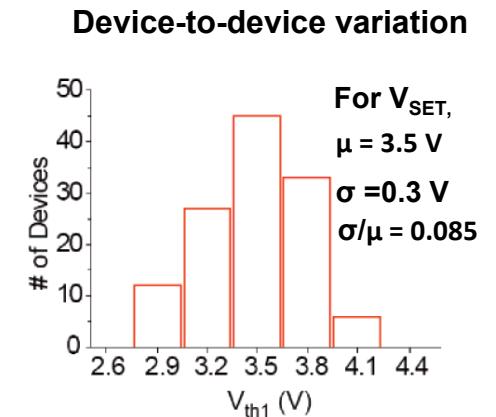
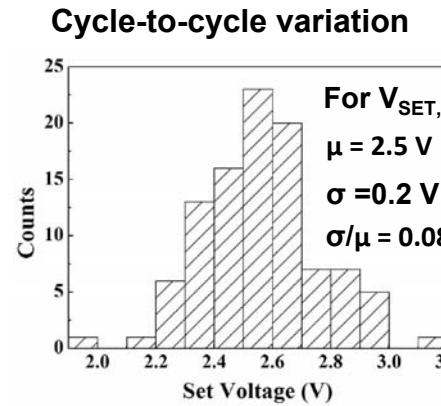
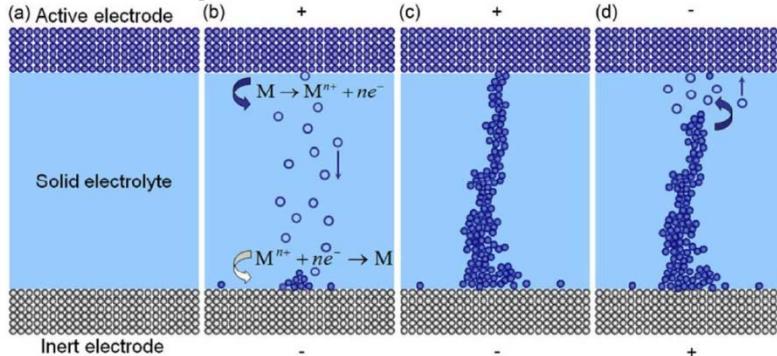
- Good endurance and retention
- Device non-uniformity  
**(Cycle-to-cycle / Device-to-device)**
  - Conductive filament is not confined in single path that cause stochastic uncorrelated switching events .
- Low On-off ratio
  - Digital: ~10 / Analog: ~2



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



# Conventional ReRAM devices- Electrochemical Metallization Memory (ECM)



## ■ 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

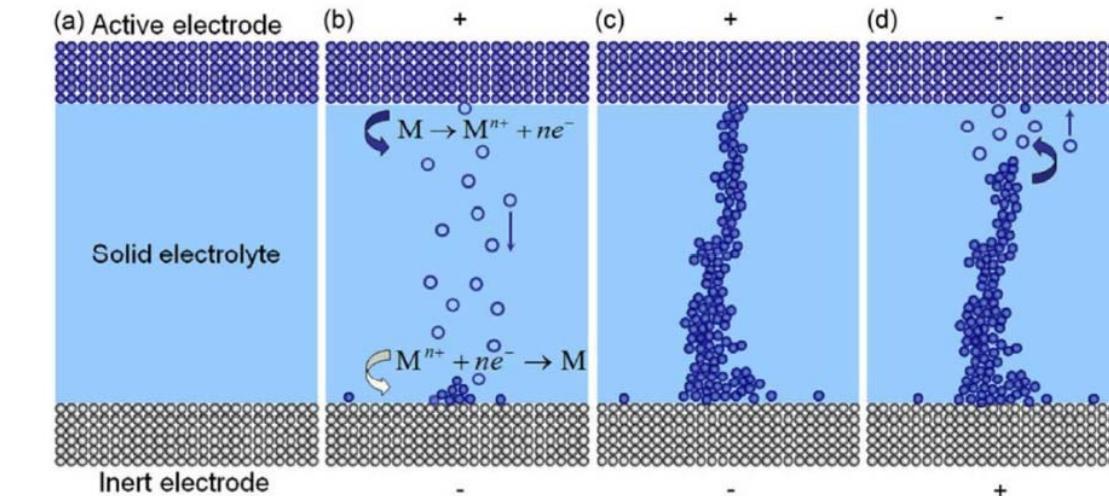
(Cycle-to-cycle / Device-to-device)

## ■ Retention/Endurance trade-off

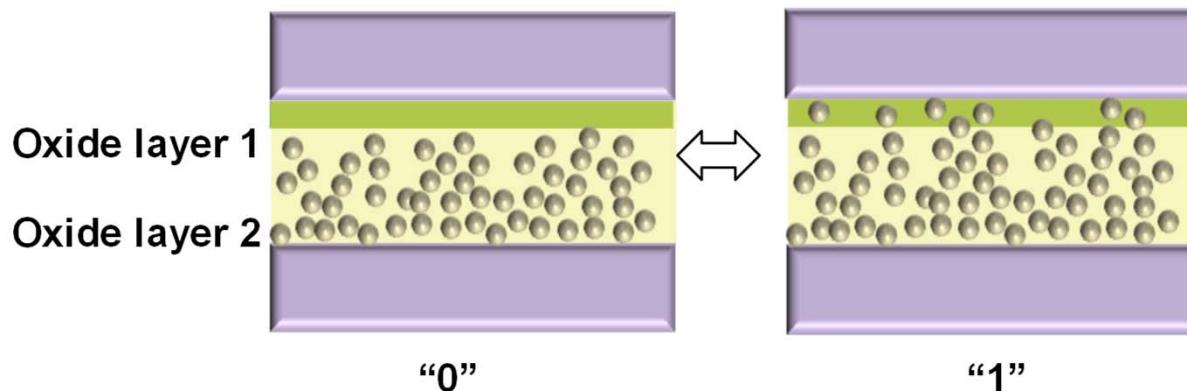
- Weak Ag-channel formation enhances endurance but reduces retention time
- Strong Ag-channel formation increases retention time but deteriorate endurance

# What is the source of device variation?

- Due to amorphous switching medium



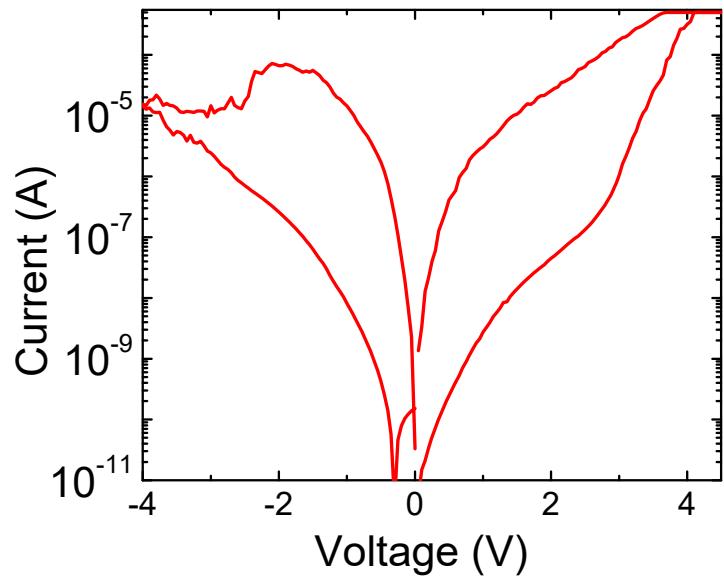
So many filament candidates



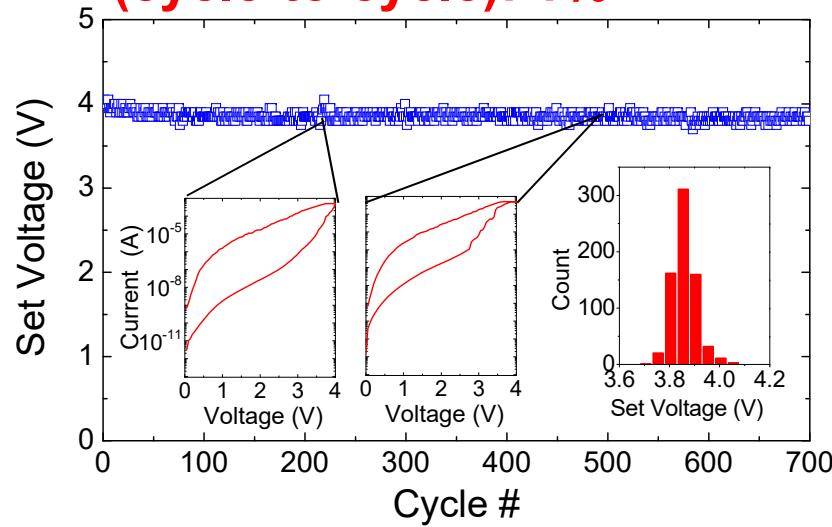
# Can single-crystalline Si do resistive switching?



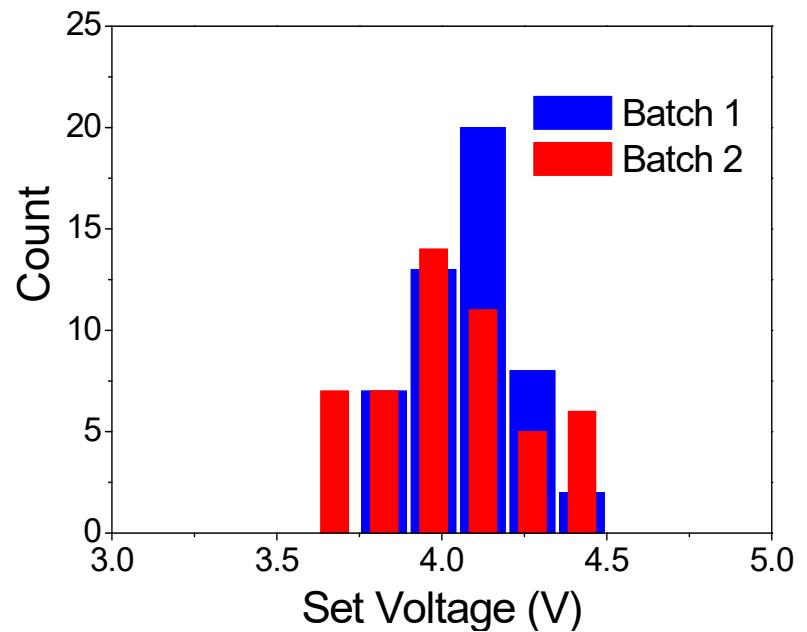
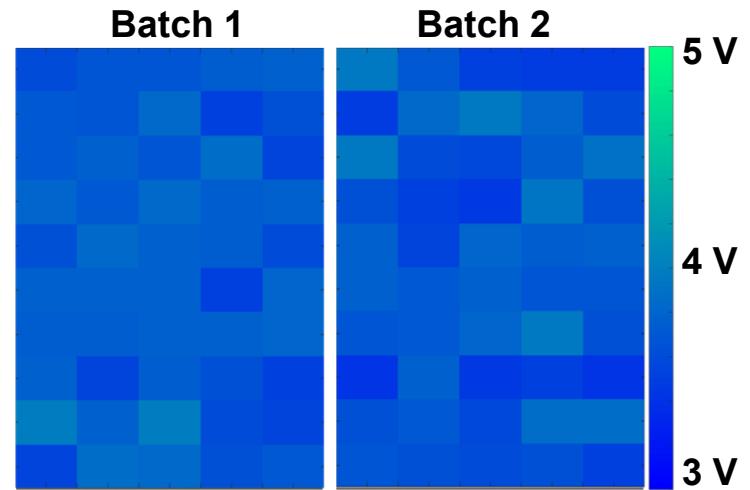
On-off ratio >  $10^4$



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



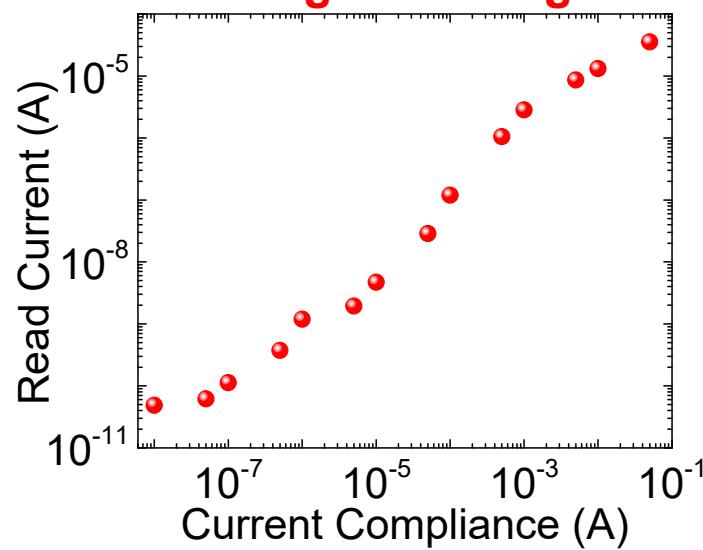
Spatial set V variation  
(device-to-device): 4%



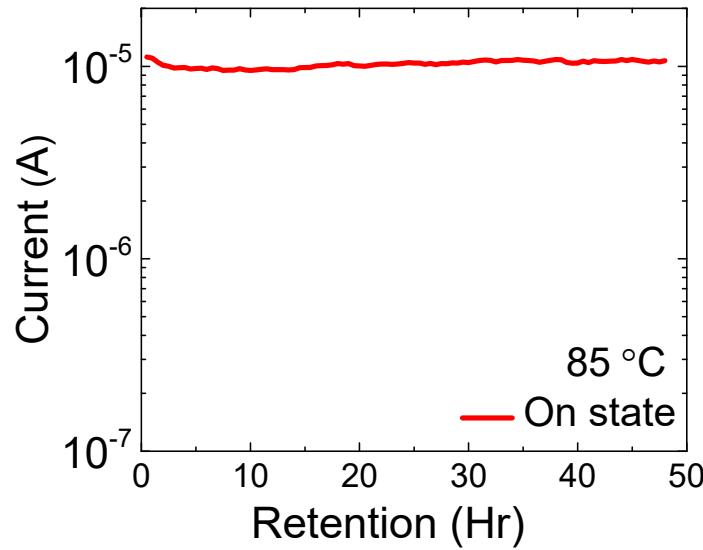
# Introduction of epitaxial RAM (epiRAM) for digital



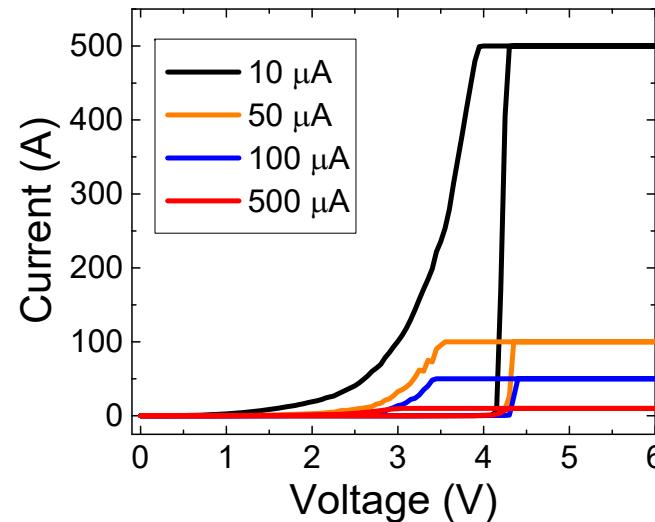
Multilevel storage from self-limiting filament growth



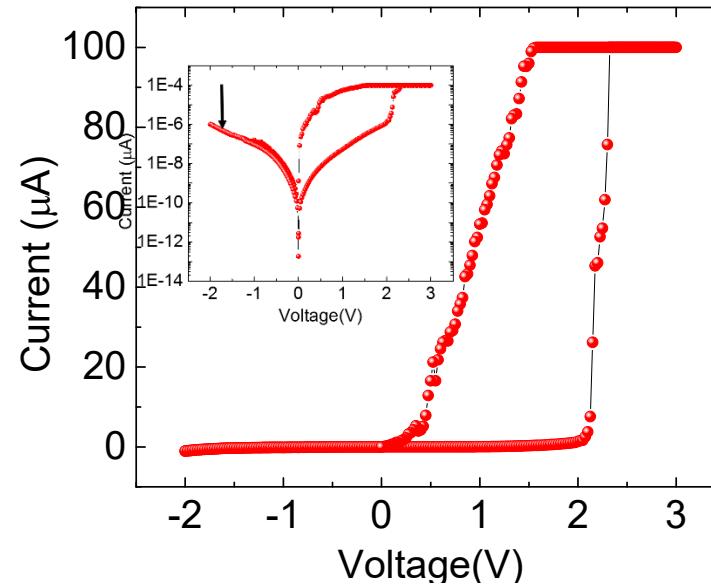
Long retention: Two days at 85°C



Reliable switching with different c.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
<b>OURS</b>	Excellent	Excellent	Excellent	High	Excellent	High	Excellent



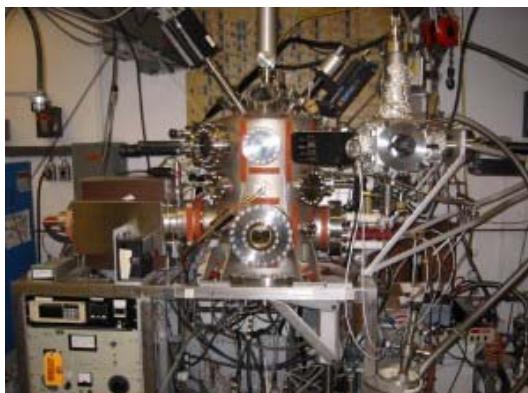
This will enable large-scale memory arrays  
for digital application as well as for neuromorphic computing

# Equipment

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



**2" MBE system (II-VI)**



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



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



## Collaborators

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