KU-SRCC
KOR-US Semiconductor R&D Cooperation Center
KE-SRCC
Korea-EU Semiconductor R&D Cooperation Center

The 2nd ROK-EU / ROK-US Join Researchrs Form

Semiconductor epitaxy without chemical bonds on wafers for 3-dimensional vertical heter-integration

(Feat. Remote/van der Waals epitaxy, RGB vertical pixel, 5000 ppi)

June 16, 2025 (14:35-14:50)

Young Joon Hong* (홍 영 준)

성균관대학교
성균나노과학기술원 (SAINT), 나노공학과, 나노과학기술학과, 첨단디스플레이공학과

*email: yjhong78@skku.edu

성균관대학교 SUNGKYUNKWAN UNIVERSITY(SKKU)
SAINT 성균나노과학기술원
첨단디스플레이공학과 Dept. Display Engineering
SE3HI

Metaverse = new emerging life platform

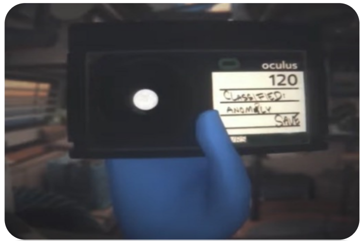
: hyper-connective, ultrarealistic virtual universe

Important tech for metaverse devices:
- Display
- Communication
- Mobile computer
- Sensor/ actuator
- Battery

The **metaverse** (a portmanteau of "meta-" and "universe") is a hypothesized iteration of the internet, supporting persistent online 3-D virtual environments through conventional personal computing, as well as virtual and augmented reality headsets. Metaverses, in some limited form, are already present on platforms like VR Chat or video games like 'Second Life’. [from Wikipedia]

Specifications for immersive see-through AR glasses

: highly bright, high pixel density, lightweight full-color light emitters are necessary

Use environment	Focal distance	Lightweight	Resolution	Viewing angle
				
indoor/cloudy	2~3m	> 500g	~ 2K	52°
				
Outdoor/daylight	30cm ~ ∞	< 40 g	> 4K	IMAX 60°(AR)/120°(VR)
Highly bright	**Multi focus optics**	**Thin/light**	**High definition**	**High angular density**
High brightness, lightweight light emitter			**Ultrafine pixel**	

Courtesy of Prof. Y. J. Choi @ Sejong Univ.

How bright light sources are needed for see-through AR glass ?

: > 1M nit at least

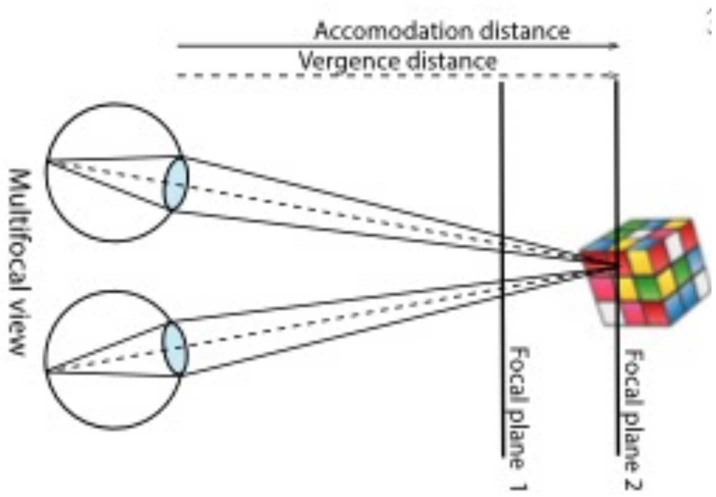
To ensure clear color symbology in sunny outdoor conditions, a brightness of at least maximum 2,000 nits (as perceived by the eye) is required

$$\text{(Brightness reaching to eye)} = \frac{\text{(Brightness of projector display)} \times [1 - \text{(Optical loss@optical elements)}]}{\text{Number of foci}}$$

> 2,000 nit

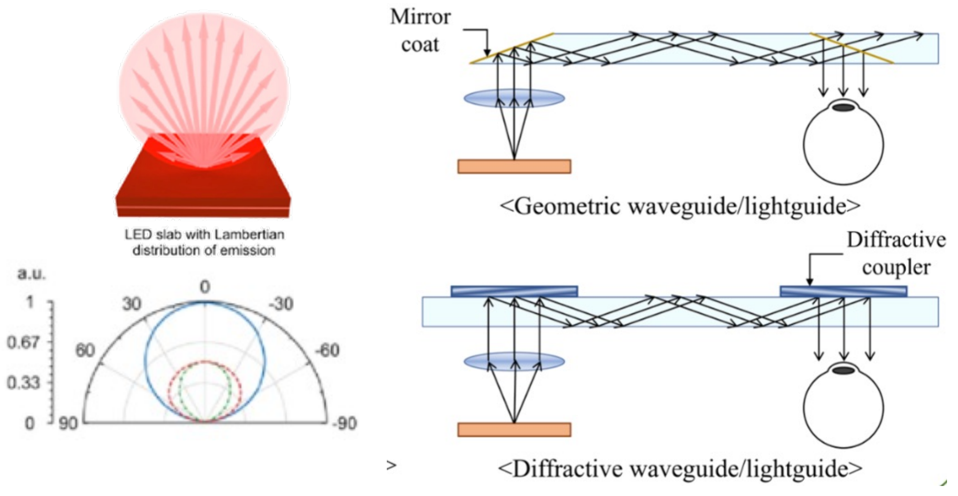
$$\text{(Brightness of projector display)} = \text{(No. of foci)} \times \text{(2,000 nit)} / [1 - \text{(optical loss @ OE)}]$$

- Number of foci > 5 focal planes



Zhan et al, PhotoniX 1, 10 ('20)

- ~ 99% optical loss @ OE (∵Lambertian LED emission)

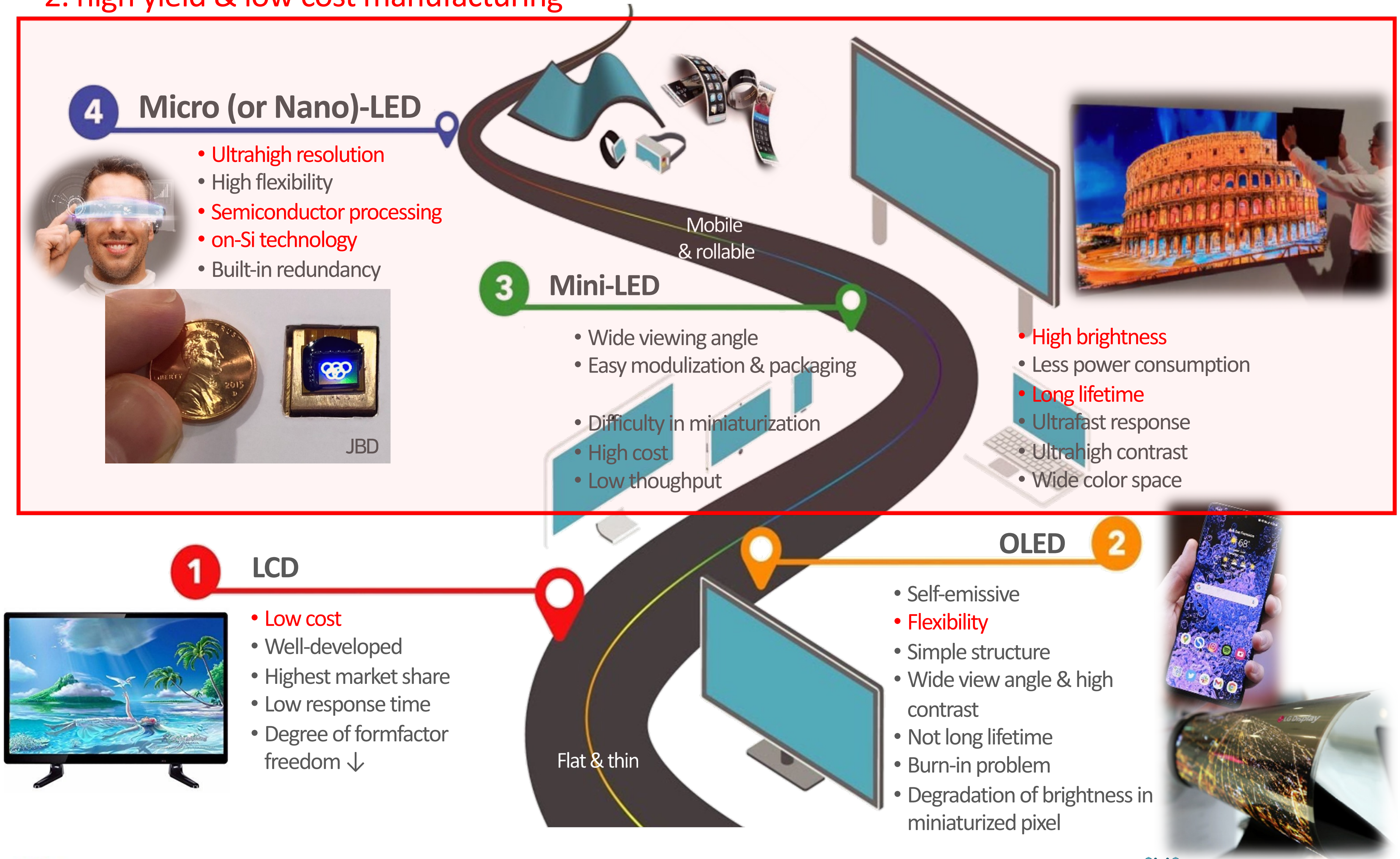


ACS Appl. Opt. Mater. 2, 1247 ('24)

$$\text{(Brightness of projector display)} = 5 \times \text{(2,000 nit)} / [1 - 0.99] = \textbf{1 Mnit (@ Max.)}$$

Candidates of flat-panel display platforms for AR/MR displays

1. Ultrahigh definition (超高精細) / high brightness / low power consumption imaging
2. high yield & low cost manufacturing



4 Micro (or Nano)-LED

- Ultrahigh resolution
- High flexibility
- Semiconductor processing
- on-Si technology
- Built-in redundancy

3 Mini-LED

- Wide viewing angle
- Easy modulization & packaging

- Difficulty in miniaturization
- High cost
- Low thoughput

- High brightness
- Less power consumption
- Long lifetime
- Ultrafast response
- Ultrahigh contrast
- Wide color space

1 LCD

- Low cost
- Well-developed
- Highest market share
- Low response time
- Degree of formfactor freedom ↓

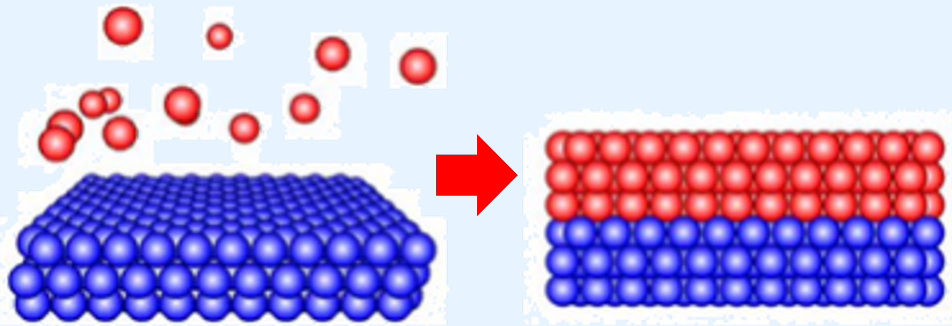
OLED 2

- Self-emissive
- Flexibility
- Simple structure
- Wide view angle & high contrast
- Not long lifetime
- Burn-in problem
- Degradation of brightness in miniaturized pixel

Epitaxy vs. Mass-transfer–assembly method for multifunctional devices

Epi (ἐπί) = upon

Taxy (τάξις) = ordered manner



Advantages:

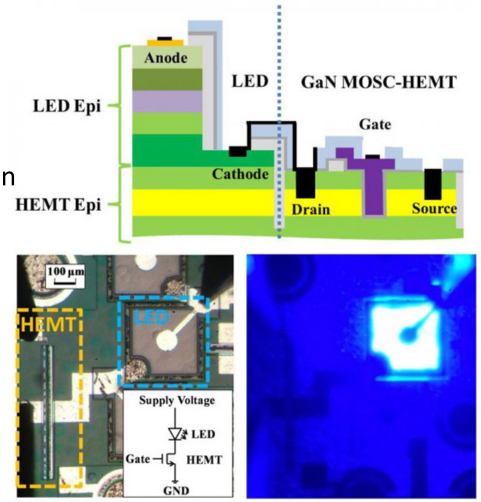
- Single crystalline overlayer on single crystal wafer
- Heteroepitaxy
- Integration
- Abrupt junction (vs. ion implantation)

Heteroepitaxial thin film growth: planar 2D growth

- Double heterostructure-based high-speed electronics and quantum well laser (Alferov & Kroemer, '63)
- Superlattice & negative differential conductance (L. Esaki, '70)
- Fractional quantum Hall effects (Tsui, Stormer & Gossard, '82)
- III–N Green, Blue LEDs/LDs (Akasaki, Amano & Nakamura, early 90s)

Multi-stack epitaxy for heterogeneous integration

For multi-function integration

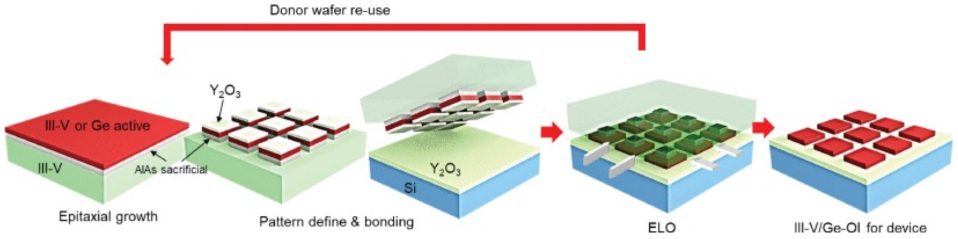


"GaN LED–HEMT on GaN chip"
Appl. Phys. Lett. 102, 192107 ('13)

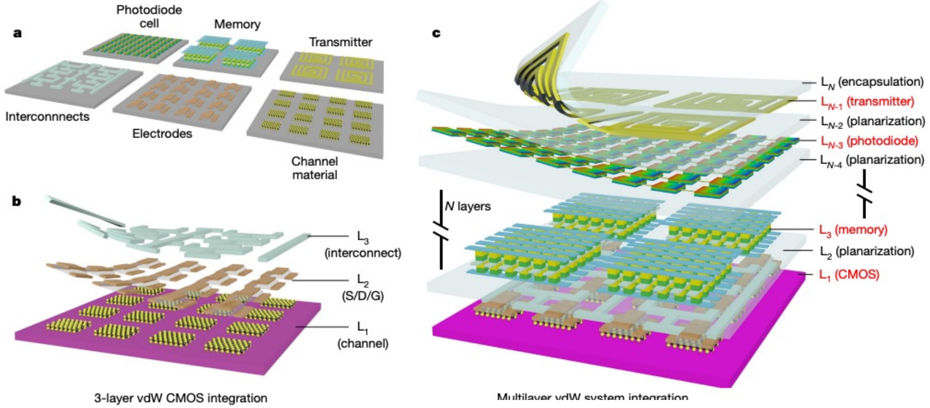
Stamping–Printing

Nat. Mater. 5, 33 ('06)

"Chip-to-plate" mass-transfer & assembly



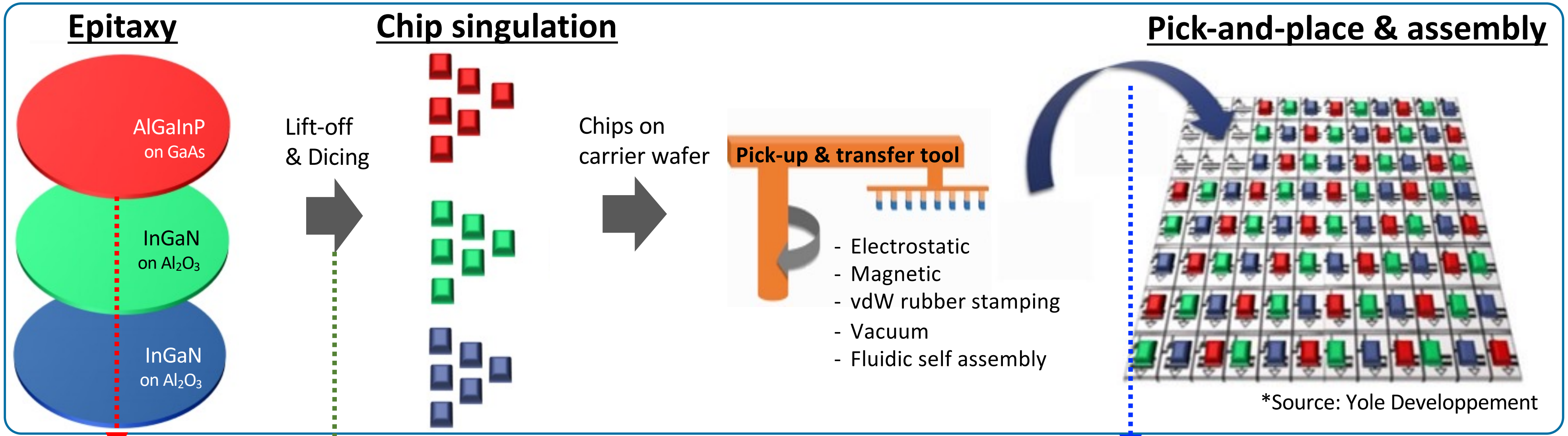
IEEE J. Electron. Dev. Soc. 6, 579 ('18)



"vdW integration" Nature 567, 323 ('19)

How to manufacture micro-LED displays

: Problem in "chip-to-plate" transfer & assembly technique for high precision



Epitaxy

Chip singulation

Lift-off & Dicing

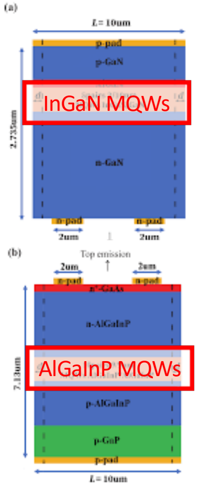
Chips on carrier wafer

Pick-and-place & assembly

- Electrostatic
- Magnetic
- vdW rubber stamping
- Vacuum
- Fluidic self assembly

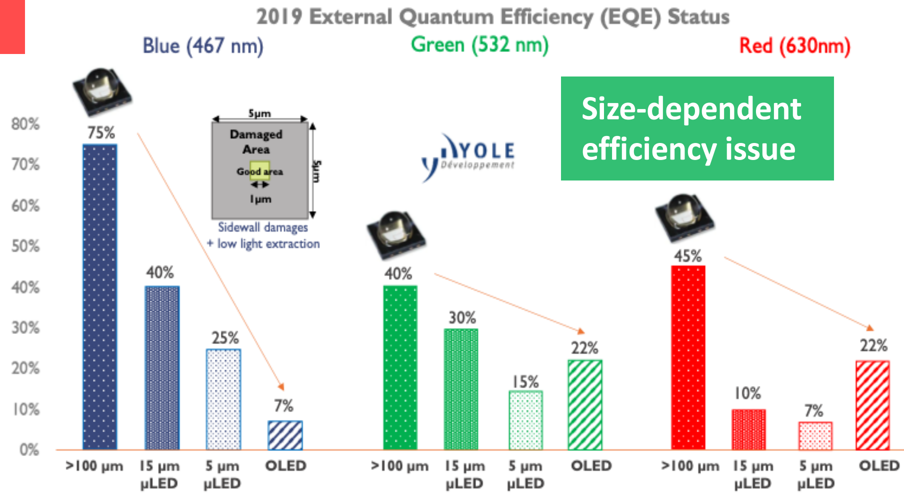
*Source: Yole Developpement

Red material issue (III-P → III-N)



Processes 10, 489 ('22)

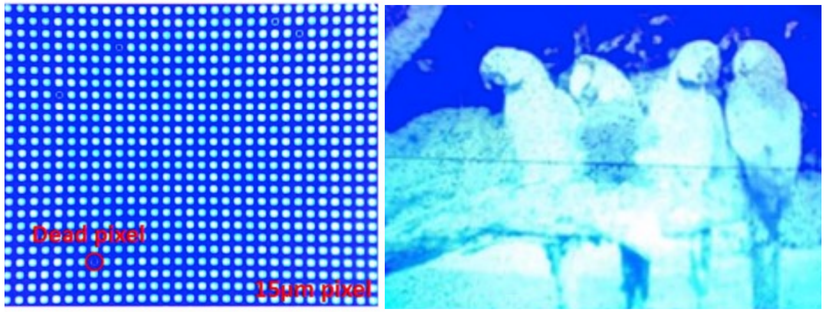
- **Different MOCVD systems**
- **Different LED geometry**



Size-dependent efficiency issue

- **Dicing → sidewall damage, dead area**
- **Green & red micro-LEDs are not good**

High precision & High yield assembly issues



Qi et al. Photon. Res. 11(1), 109 ('23)

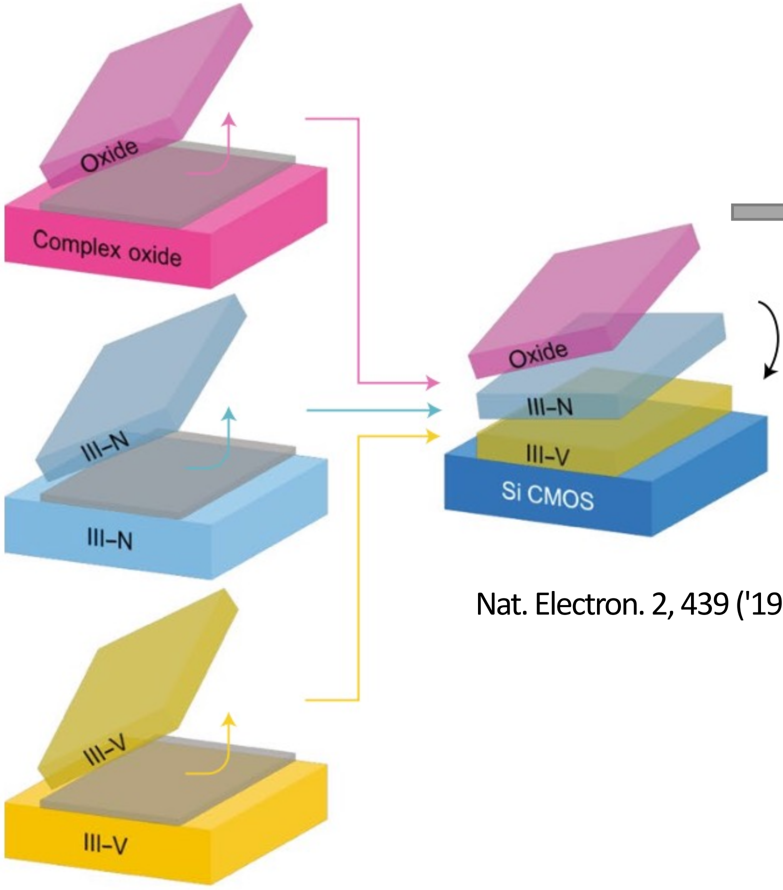
- **MOST COST-INTENSIVE PROCESS**
- **State-of-the-art transfer (mechanical) alignment accuracy: currently ±1.5 µm [Xdisplay ±0.25 µm, ('24 IDW)]**
- **Rework or replacement of failure**

Strategy for high density, high precision integration of R/G/B LEDs

: Membrane stacking & micro-lithographic patterning (not 'chip-to-plate' method)

Non-covalent epitaxy[*]

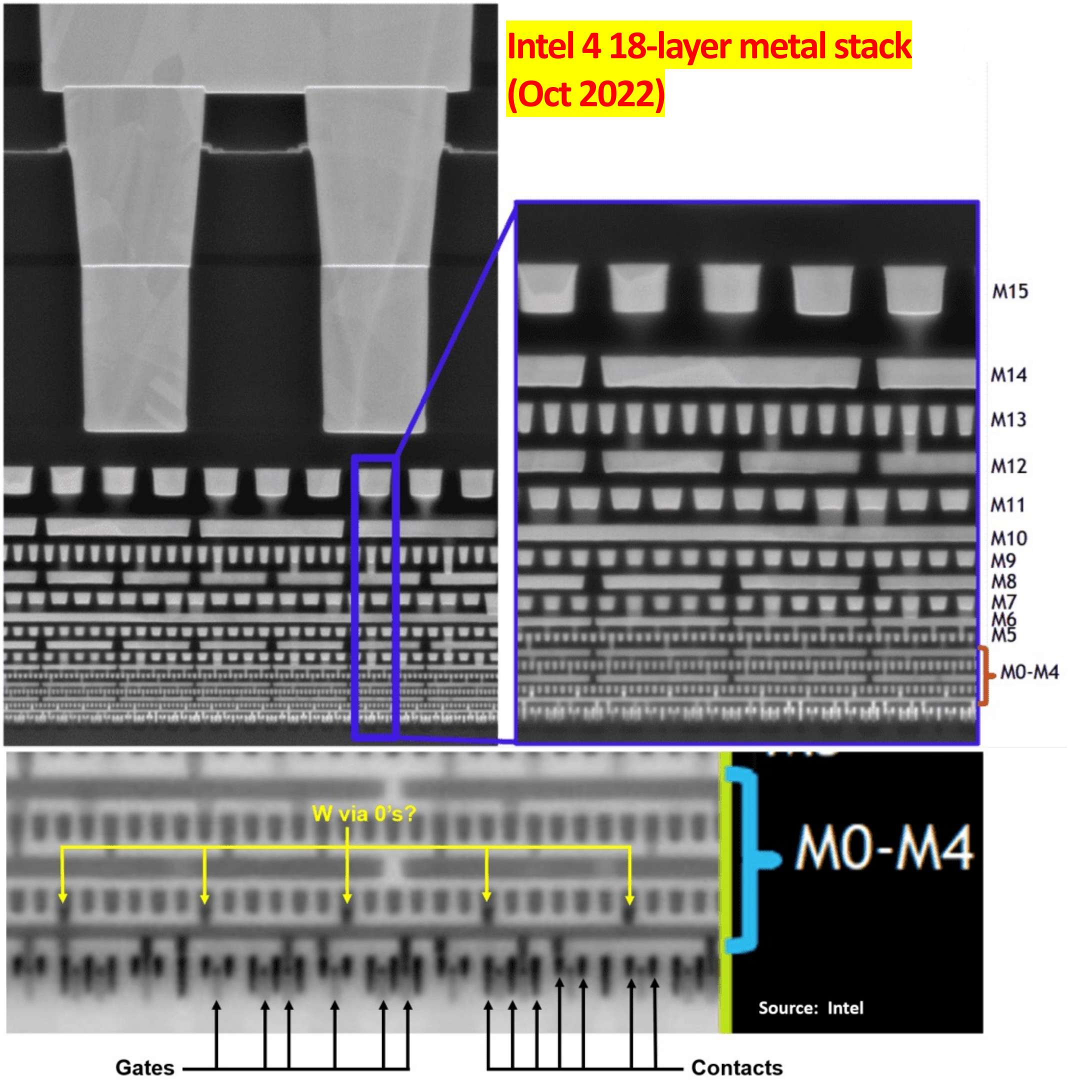
- ✓ No high energy or chemical separation
- ✓ Easy to vertical multi-stack



Nat. Electron. 2, 439 ('19)

[*] Non-covalent epitaxy = non-chemical bonded epitaxy
1. van der Waals epitaxy
2. Remote epitaxy

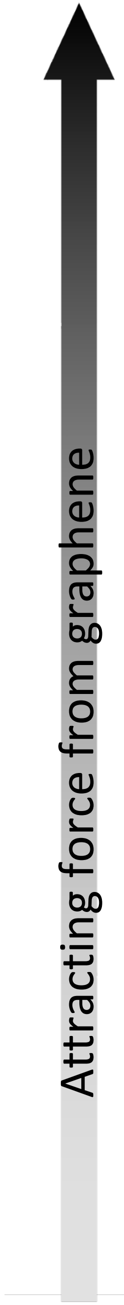
Photolithographic patterning



Intel 4 18-layer metal stack (Oct 2022)

Gate pitch = 50 nm **M0 pitch = 30 nm**

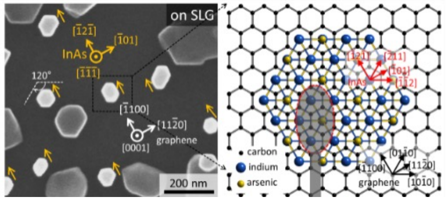
Epitaxy on graphene-on-wafer: roles of graphene



$F_{substrate} < F_{graphene}$: Growth seed → vdW epitaxy

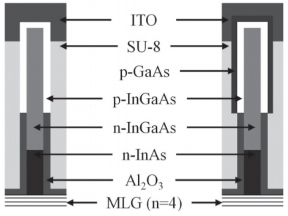
- Unconventional, noncovalent heteroepitaxy [Koma *et al. Microelectron. Eng.* **2**, 129 ('84)]
- Energy minimization with adatom on hollow, bridge or ball-top of carbon honeycomb drives epitaxy

<Use of single-layer graphene>



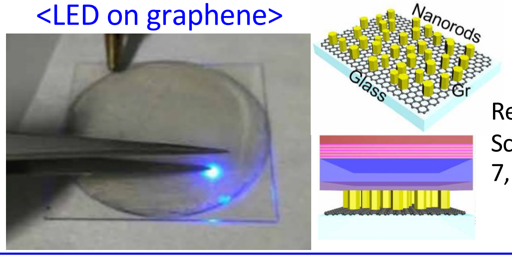
ACS Nano 5, 7576 ('11);
Nano Lett. 12, 1431 ('12);
Adv. Mater. 25, 6847 ('13)

<NW solar cell on graphene>



Mohseni *et al.*
Adv. Mater.
26, 3755 ('14)

<LED on graphene>

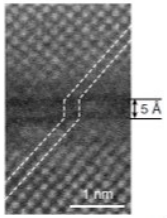


Ren *et al.*,
Sci. Adv.
7, eabf5011 ('21)

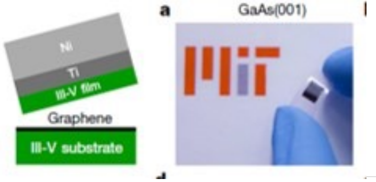
$F_{substrate} > F_{graphene}$: Lattice transparency → Remote epitaxy

- Interacting force from substrate penetrates graphene, which enables copy of crystallographic registration from substrate to overlayer across graphene

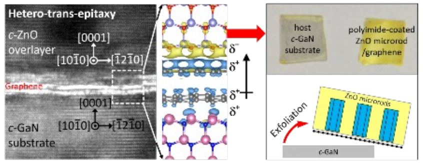
<Transferable single crystal LED>



Kim *et al.*
Nature
544, 340 ('17)

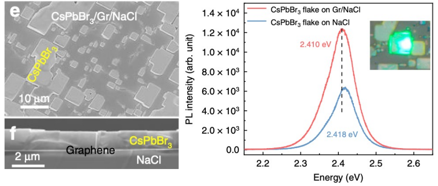


<Microrod>



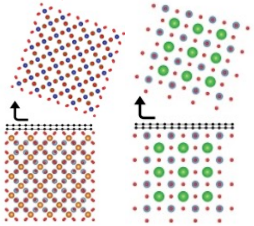
Jeong *et al.* Nanoscale 10, 22970 ('18);
Appl. Phys. Lett. 113, 233103 ('18)

<Halide perovskite>



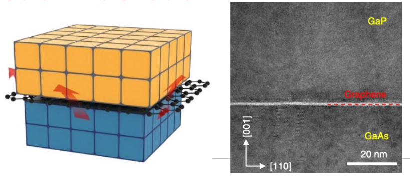
Jiang *et al.*, Nat. Commun. 10,4145 ('19)

<Complex oxides>



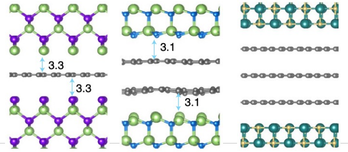
Kum *et al.*,
Nature
578, 75 ('20)

<Strain relaxation>



Bae *et al.*,
Nat. Nanotechnol.
15,4272 ('20)

<Polarity vs. graphene thickness>

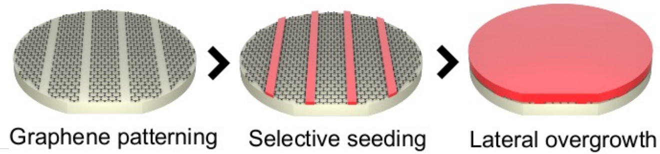


Kong *et al.*,
Nat. Mater.
17, 999 ('18)

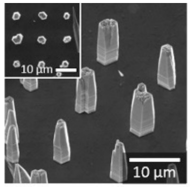
Hydrophobic surface (hard to deposit) → Growth mask for selective growth (or ELOG)

- With respect to some materials, the surface attraction is too weak to capture the adatoms so that inhibits the growth

<Selective growth through opening of graphene>



Kim *et al.*
Nat. Nanotechnol.
17, 1054 ('22)



Jeong *et al.*
ACS Appl. Nano Mater.
3, 8920 ('20)

Overall procedures for vertical pixels

I. Substrate preparation

- 2D: graphene, hBN, aBN
- Wafer: GaN/Al_2O_3, AlN/Al_2O_3, SiC, GaAs

II. Remote or van der Waals epitaxy

van der Waals epitaxy (nitrides):

- Substrate: single crystalline hBN/Al_2O_3

- Growth: *p*-GaN/MQWs/*n*-GaN/*n*-AlGaN

Remote epitaxy (nitrides):

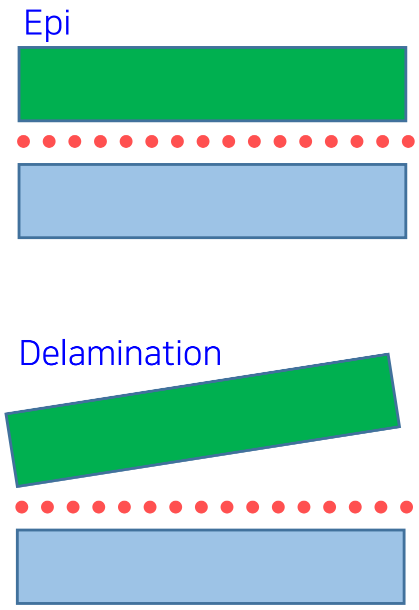
- Substrate: amorphous BN/GaN (or AlN) and graphene/SiC

- Growth: *p*-GaN/MQWs/*n*-GaN/*u*-GaN

Remote epitaxy (arsenides):

- Substrate: graphene/GaAs

- Growth: AlGaAs/GaAs heterostructure *p–n* junction



III. Device fabrication

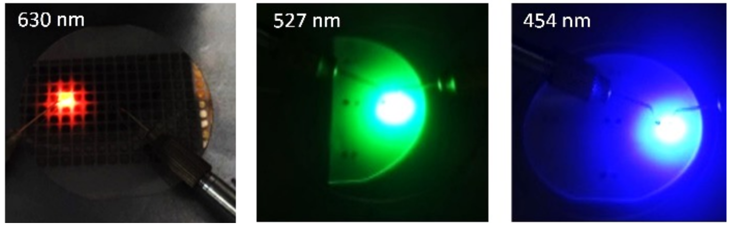
- Membrane stack and device fab.

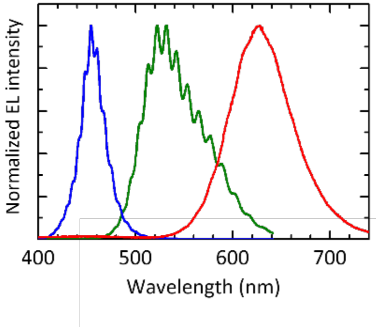
Collaboration with
Profs J. Kim @ MIT
Prof. A. Ougazzaden @ Georgia Tech Europe
Prof. K. Lee @ U of Virginia

Metal–organic vapor-phase epitaxy for GaN growth (@ SKKU)

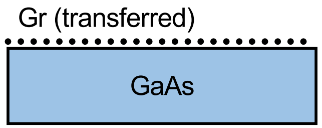
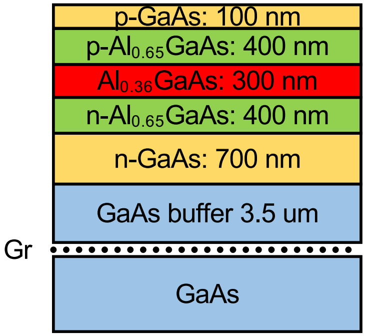
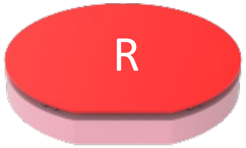
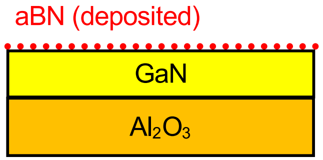
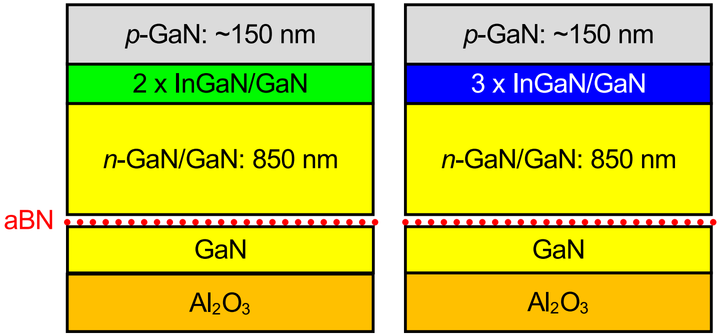
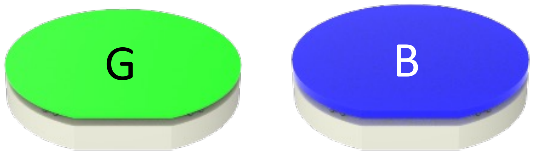
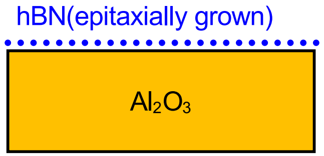
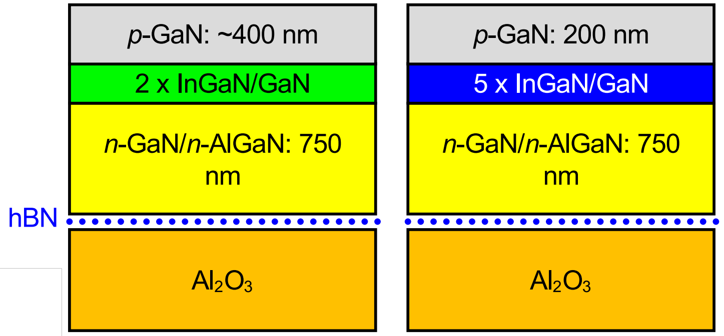
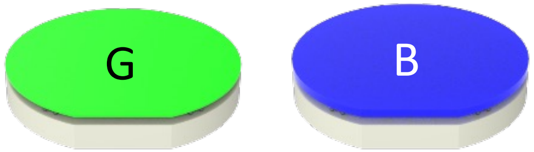
: Typical MOCVD system with close-coupled showerhead and single 2 inch wafer pocket

- Reactor: vertical, showerhead, 1×2 inch wafer, up to 1100 °C
- MO: TMGa, TMIn, Cp_2Mg - Gas: H_2, N_2, NH_3, SiH_4
- Product:
  1. R/G/B thin film LEDs (conventional epi)
  2. G/B thin film LEDs (van der Waals & remote epi)
  3. G/B microrod LEDs (remote epi)
- Safety: gas cabinet, gas detector–leak alarm system, uninterruptible power supply (UPS)
- Exhaust: pyrolytic scrubber

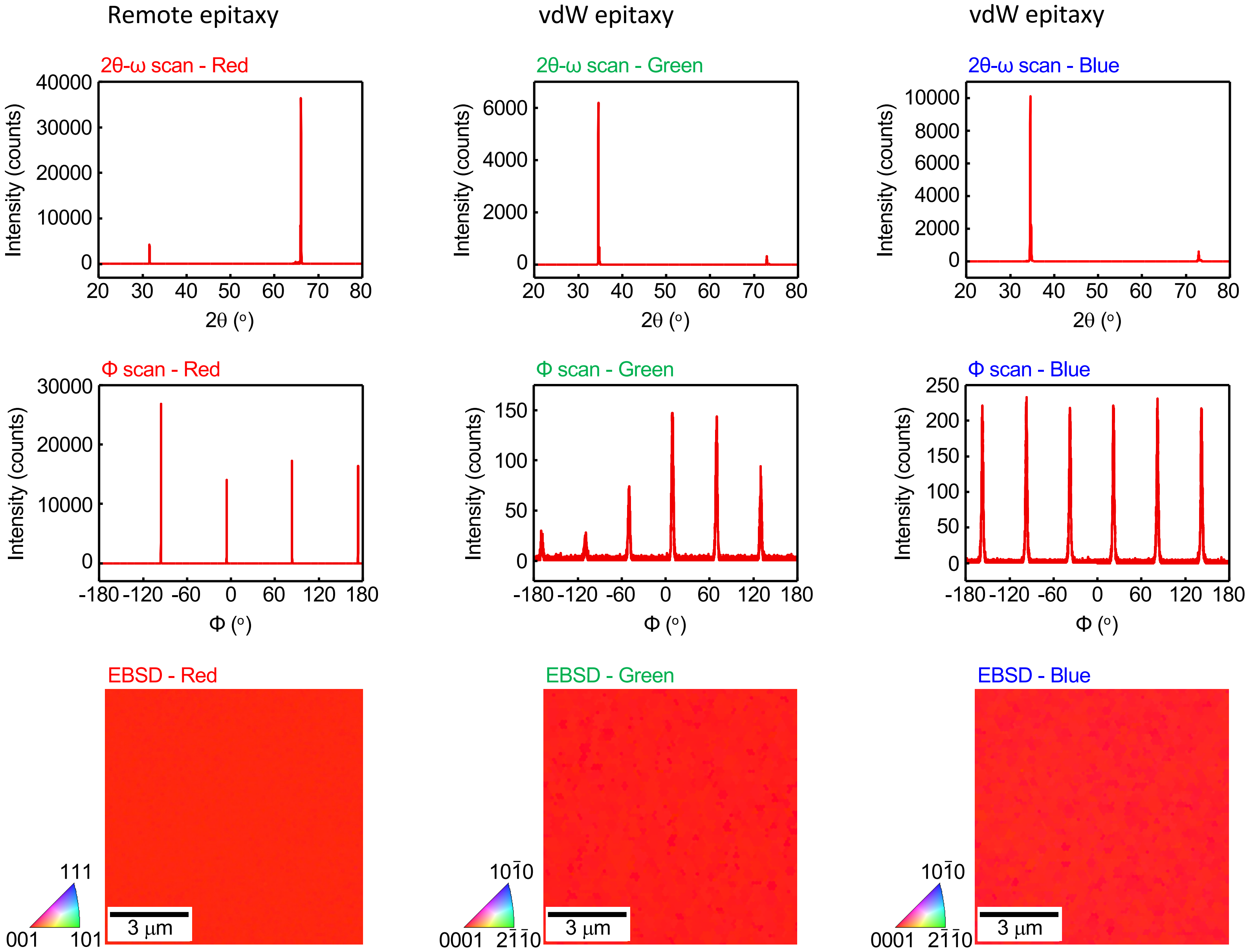




Remote & van der Waals epitaxy of R, G, and B LEDs

Substrate	Method	Epi-structure	Product
MIT  Gr (transferred) GaAs	remote epi	MIT  p-GaAs: 100 nm p-Al$_{0.65}$GaAs: 400 nm Al$_{0.36}$GaAs: 300 nm n-Al$_{0.65}$GaAs: 400 nm n-GaAs: 700 nm GaAs buffer 3.5 um Gr GaAs	 R
MIT UoV  aBN (deposited) GaN Al$_2$O$_3$	remote epi	Sejong  *p*-GaN: ~150 nm 2 x InGaN/GaN *n*-GaN/GaN: 850 nm aBN GaN Al$_2$O$_3$ *p*-GaN: ~150 nm 3 x InGaN/GaN *n*-GaN/GaN: 850 nm GaN Al$_2$O$_3$	 G B
GTL  hBN(epitaxially grown) Al$_2$O$_3$	vdW epi	Green: Sejong Blue: GTL  *p*-GaN: ~400 nm 2 x InGaN/GaN *n*-GaN/*n*-AlGaN: 750 nm hBN Al$_2$O$_3$ *p*-GaN: 200 nm 5 x InGaN/GaN *n*-GaN/*n*-AlGaN: 750 nm Al$_2$O$_3$	 G B

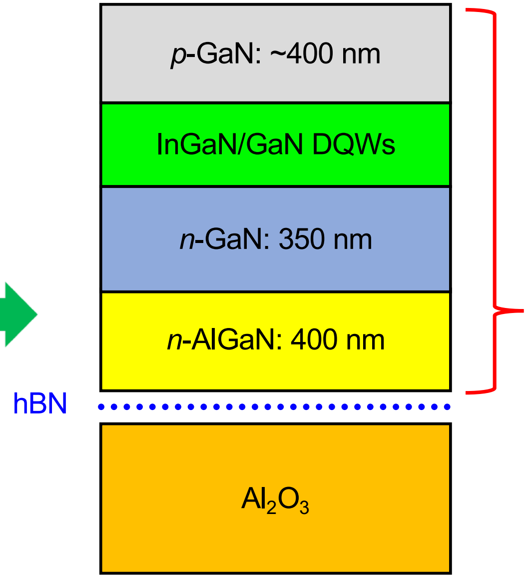
Mono-crystallinity of remote- & vdW-epitaxial LEDs

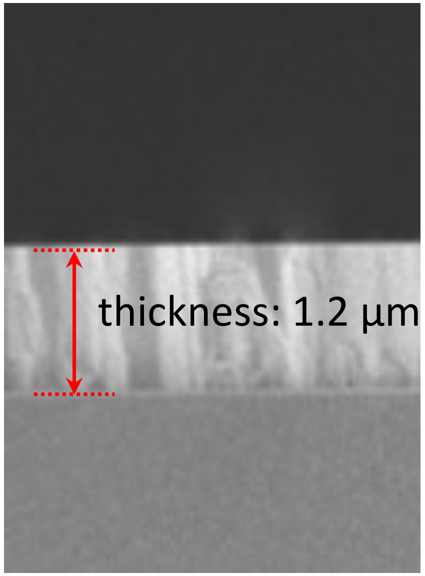


van der Waals epitaxy of InGaN/GaN green LEDs

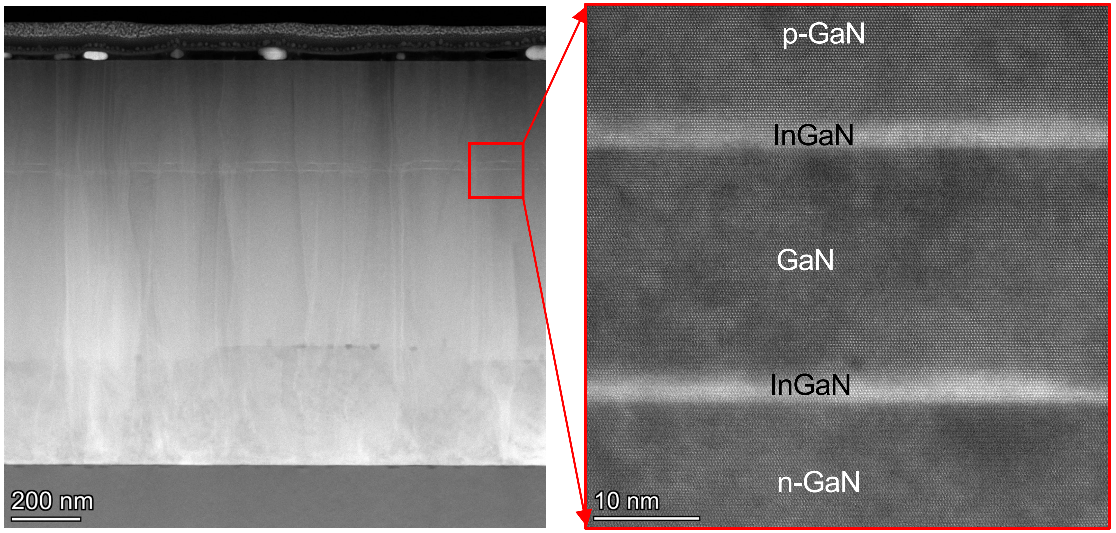
: Thin LED structure for vertical stack pixel architecture

van der Waals epitaxy

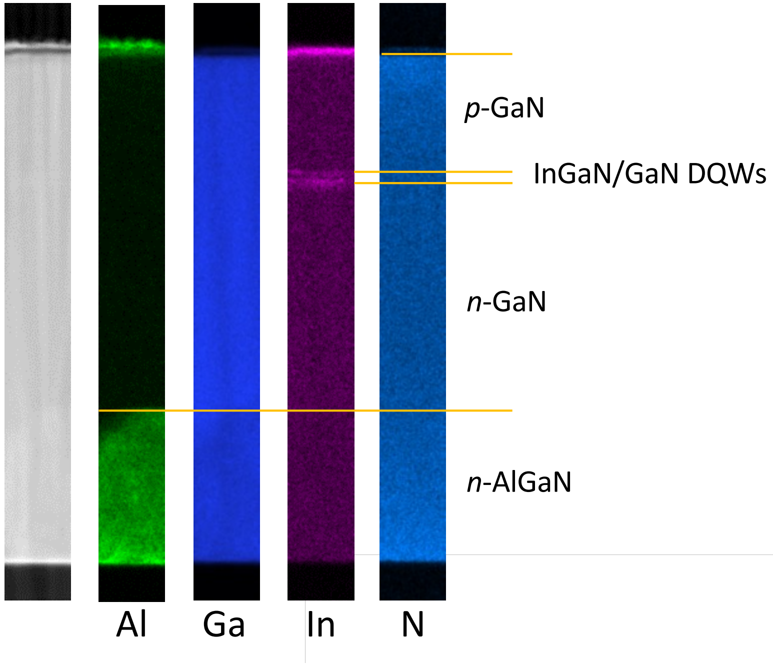




Green LED



EDS mapping



Epi-layer delamination

: Free-standing LED membrane & reuse of wafer

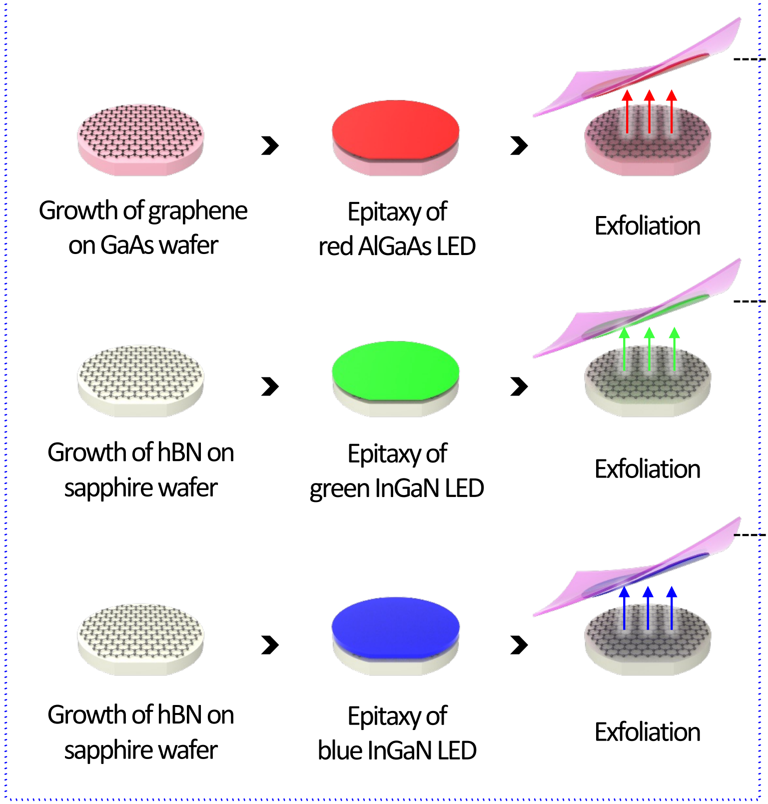
van der Waals epitaxy

- Easy, quick, and high-yield lift-off
- No residues left
- Nearly damage-free delamination
- No need for kinetic control

Vertically stacked R/G/B micro-LEDs

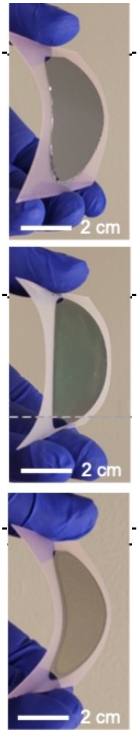
: fabricated via photolithographic patterning using an I-line stepper

2D material-based layer transfer of RGB LEDs

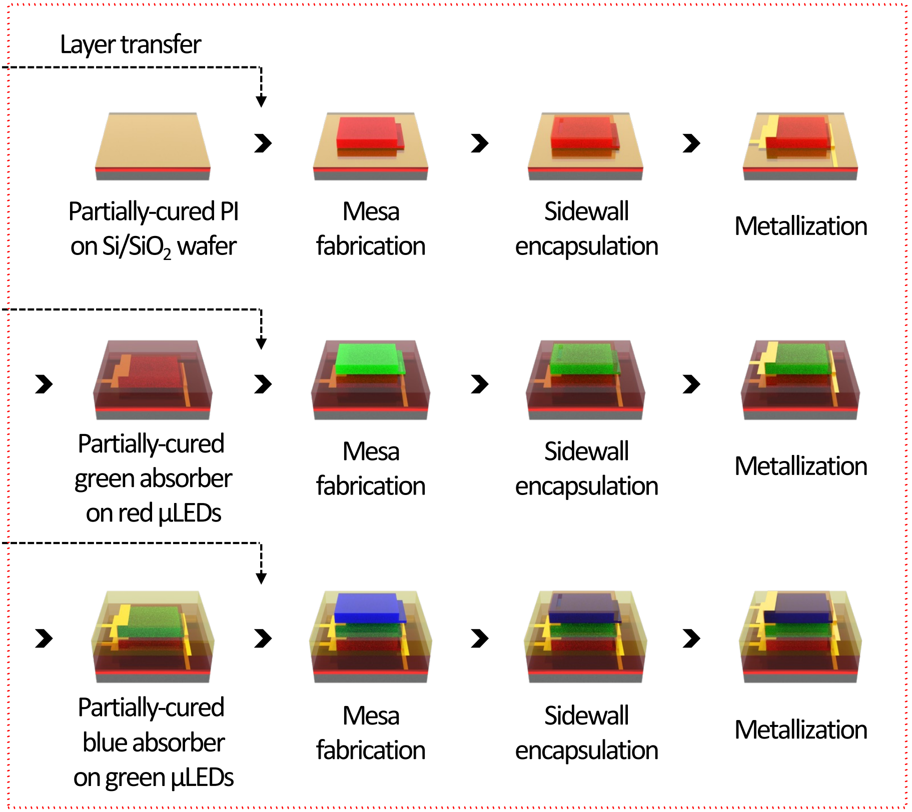

Growth of graphene on GaAs wafer → Epitaxy of red AlGaAs LED → Exfoliation

Growth of hBN on sapphire wafer → Epitaxy of green InGaN LED → Exfoliation

Growth of hBN on sapphire wafer → Epitaxy of blue InGaN LED → Exfoliation



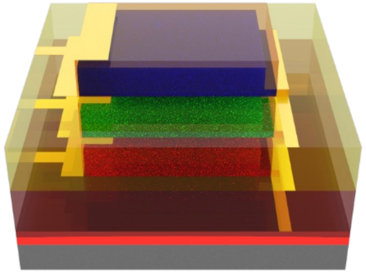
Vertical stacking and fabrication of micro-LEDs

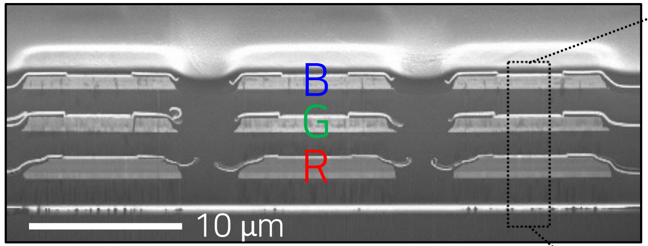

Layer transfer

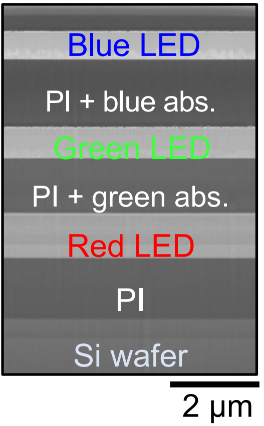
Partially-cured PI on Si/SiO$_2$ wafer → Mesa fabrication → Sidewall encapsulation → Metallization

→ Partially-cured green absorber on red µLEDs → Mesa fabrication → Sidewall encapsulation → Metallization

→ Partially-cured blue absorber on green µLEDs → Mesa fabrication → Sidewall encapsulation → Metallization

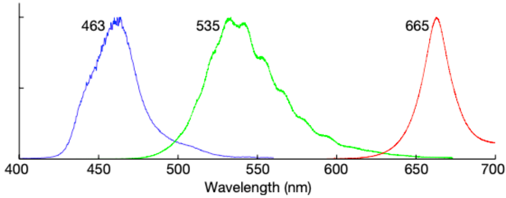






Ultrathin RGB LED layers (each 1–2 µm) → Vertical RGB stack:

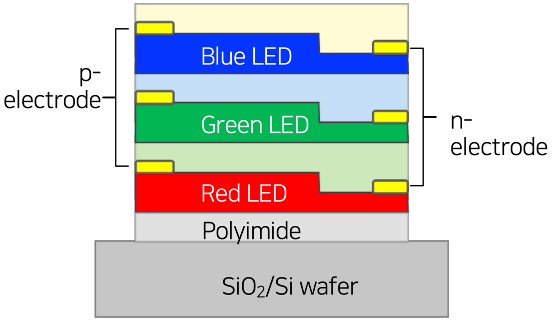
- ✓ height ~9 µm
- ✓ size ~10 µm

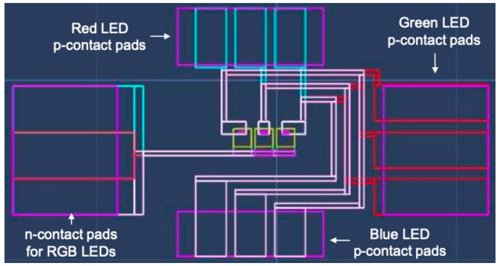


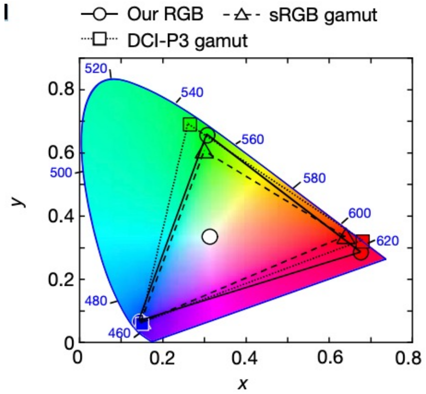
- Precise x–y position alignment
- High density vertical integration

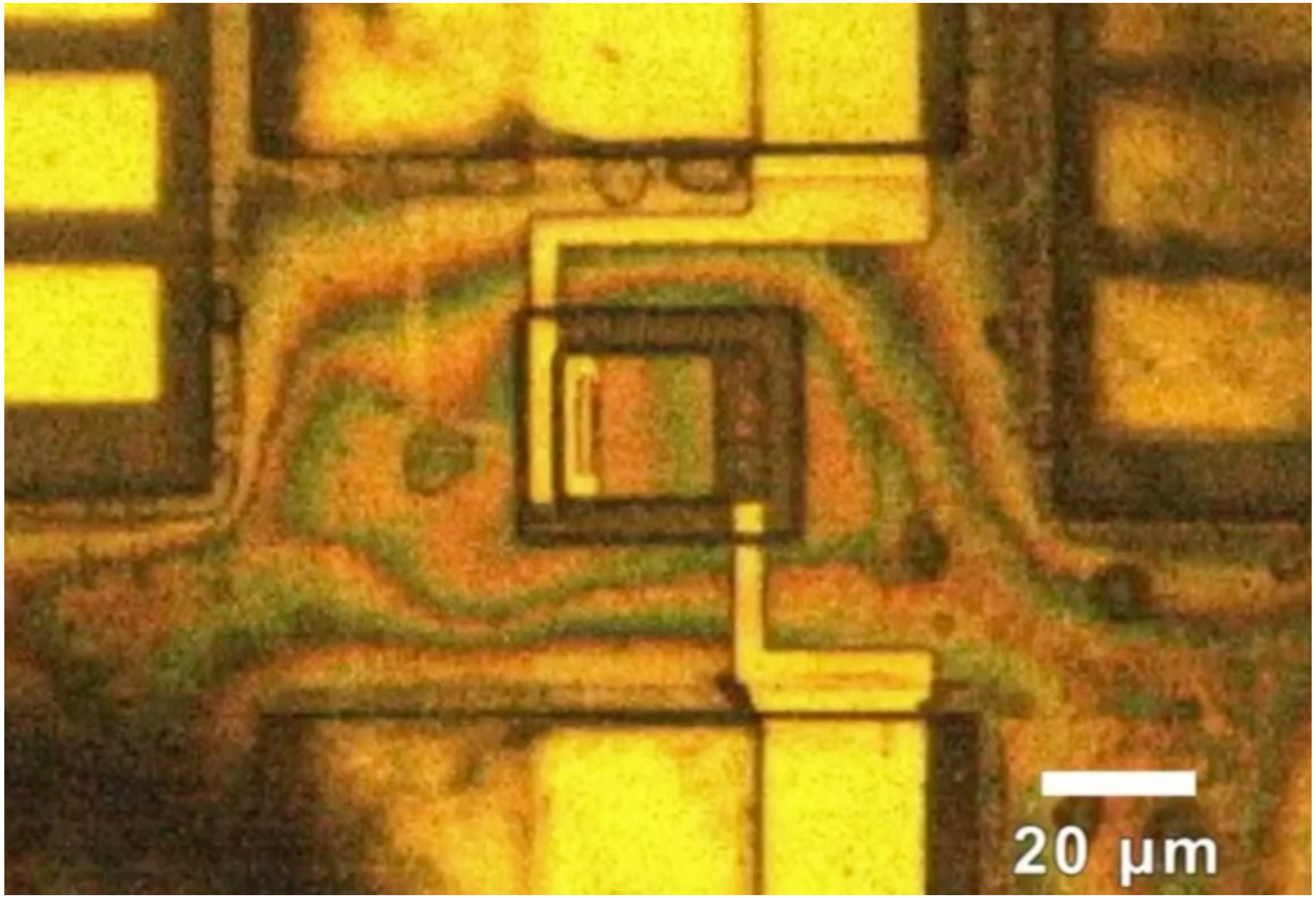
Full-color EL emission from a single R/G/B vertical pixel

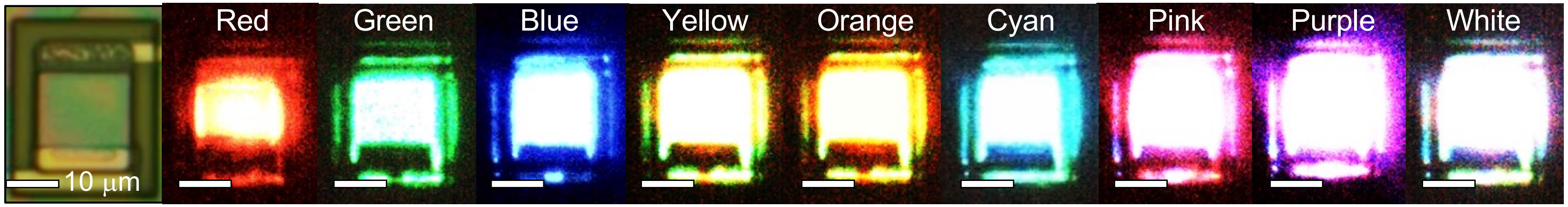
: Tandem pixel architecture





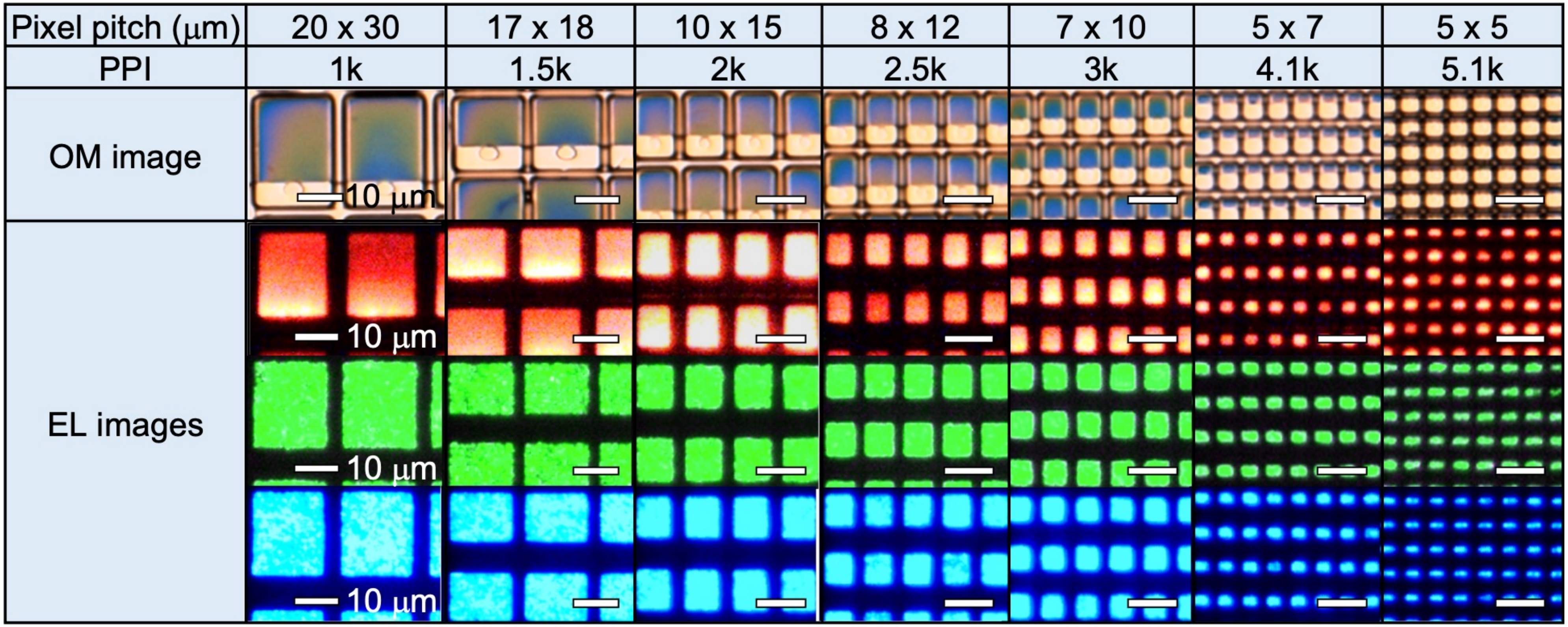






R+G B+G R+B R+G+B

Vertically stacked R/G/B micro-LEDs: high-density pixel arrays



Pixel pitch (μm)	20 x 30	17 x 18	10 x 15	8 x 12	7 x 10	5 x 7	5 x 5
PPI	1k	1.5k	2k	2.5k	3k	4.1k	5.1k

- A resolution of 5,100 ppi delivers 100 times more pixel information than the iphone 17 (458 ppi) at the same display size
- We have developed a novel method for high-density pixel fabrication, inspired by the concept of pancake stacking followed by precise slicing
- This approach offers a cost-effective, simple, fast, and accurate solution for producing ultra-high-resolution LED displays
- The vertical pixel architecture we employ is particularly advantageous for immersive displays, delivering at least three times the resolution compared to conventional horizontal pixel array structures

Toward “beyond CMOS” & “more than Moore”

3d integrated circuits (design and packaging)

(State-of-the art) System-in-package (w/ TSV & interposer)

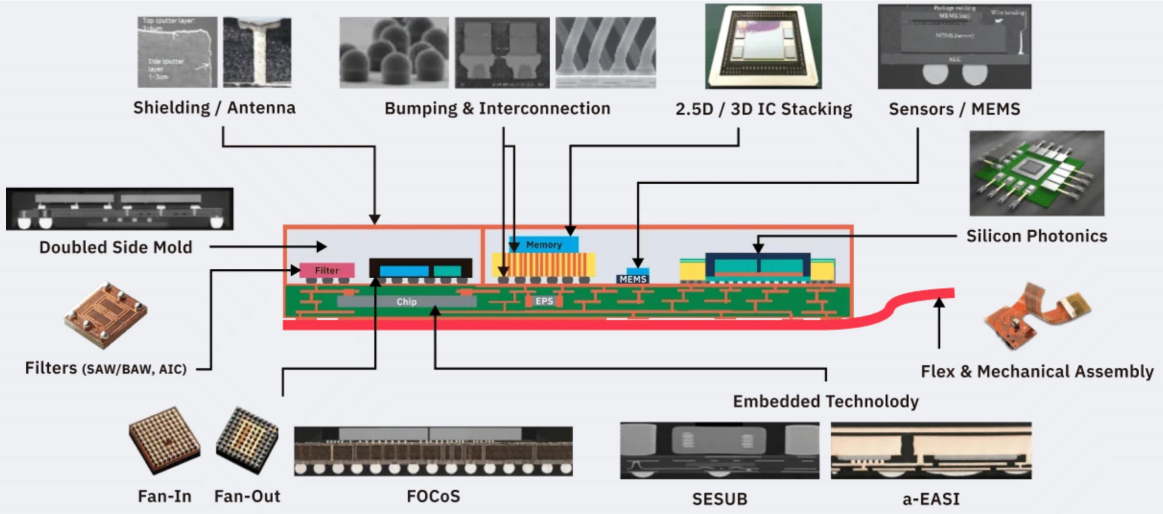


Image from ASE

Intel 4 (Oct 2022)

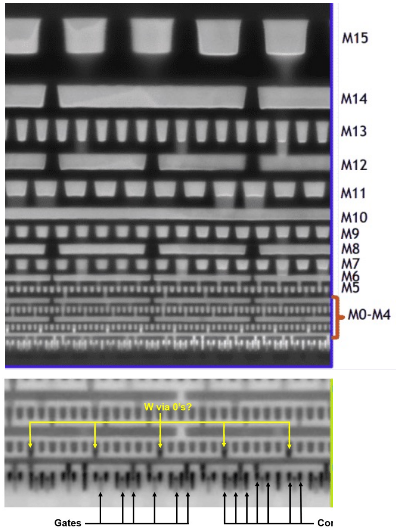
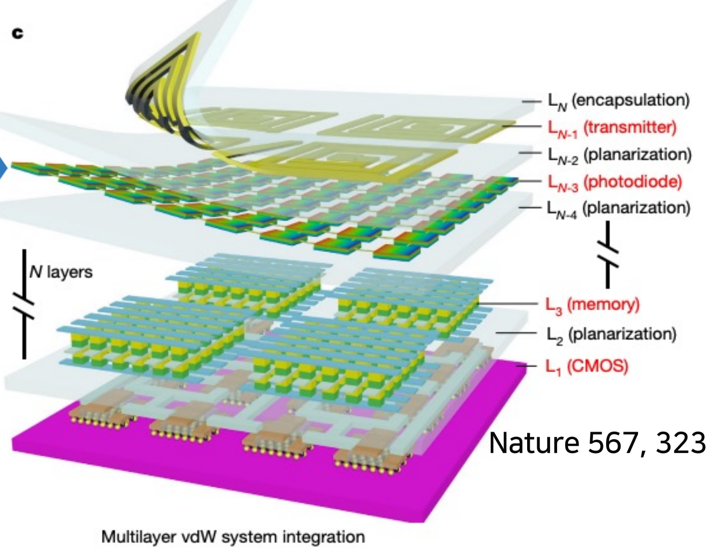


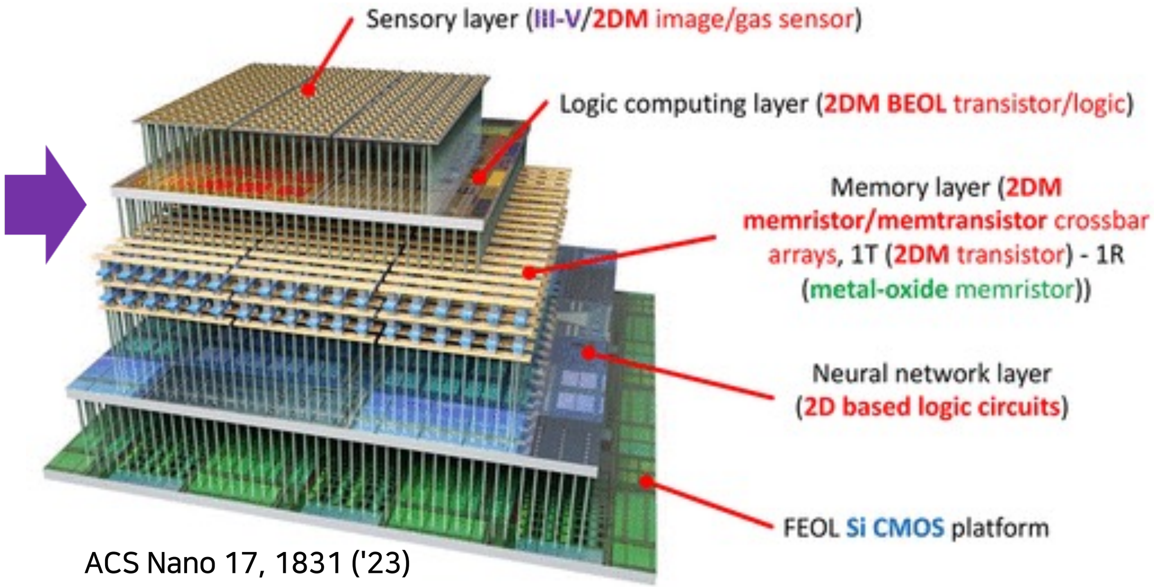
Image from Intel

(Current R&D) Chip-to-plate stack & vdW integration



Nature 567, 323 ('19)

(To be) 3d hetero-integrated circuits on one chip



ACS Nano 17, 1831 ('23)