plessey

15th Anniversary HVM 2017 & 4th Graphene New Materials Conference
2-3 November 2017 Cambridge, UK
www.cir-strategy.com/events

GaN on Silicon
Smart Technology but does it have a Bright Future ?

Dr. Keith Strickland
CTO
Plessey Semiconductors

The technology of light

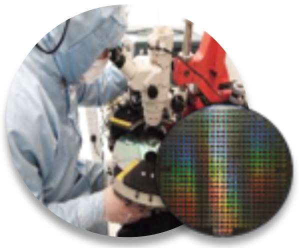
Plessey: An Innovative Technology Company

Plessey is an innovative technology design and manufacturing company

- Globally recognised British brand with significant manufacturing facilities in Plymouth (UK)

World class GaN-on-Silicon platform manufacturing technology for SSL, power electronics and emerging markets (Micro displays)

- In March 2013 Plessey launched world's first available GaN on 6-inch silicon LED products
- GaN on Silicon USPs in conjunction with silicon / IC industry advanced processing/packaging – delivering differentiated SSL solutions
- Provides integration solution for smart LED lighting and cost advantage over traditional LED manufacturing technologies
- Demonstrating LED performance equivalent to incumbent technologies on sapphire and SiC
- **Early developments for:**
  - **SCALE - Growth on 200mm wafers (first trials completed with equivalent 150mm wafer performance)**
  - **NEW MARKET OPPORTUNITY - Micro LED technology for high resolution, high luminance display technology (Smart watch, VR, AR…..)**



Plessey re-launched from the Swindon and Plymouth facilities

Market-leading sensor technology developed alongside legacy product sales

UNIVERSITY OF CAMBRIDGE

Acquisition of CamGaN provides access to ground-breaking LED technology

Transfer of experimental recipe onto production tool completed

Plessey doubles efficacy within the year, from 32 to 64lm/W

Plessey produces world's first commercial LEDs manufactured on 6" (150mm) diameter silicon substrates

Mainstream GaN-on-Si production

Expanded product range – Power LEDs

Efficacy at 130lm/W, and higher in lab

i²LED technology :-

Orion module launch

High Power LEDs launched

Advanced packaging solutions

Extension to 8 inch wafers

Integration for Smart lighting

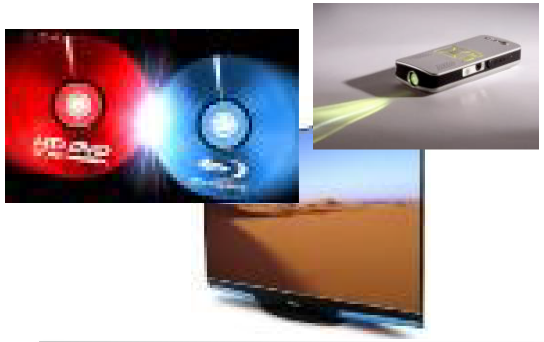
Micro LEDs

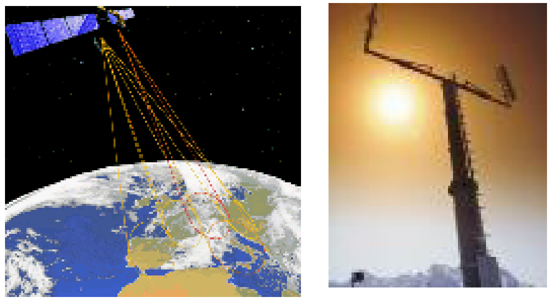
2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 and ONWARDS

Why GaN ?

GaN is one of a number of wide band gap semiconductors with multiple applications

Laser Diodes	LED	Power	RF Power
Data storage Projectors Lighting !	SSL	Power Supplies UPS EV / HEV	3G/4G comms Sat Base stations



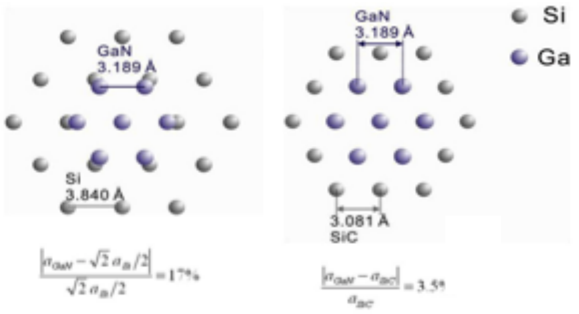


Material substrates

Laser Diodes	LED	Power	RF Power
Bulk GaN	GaN on Sapphire	SiC	GaN on Silicon
	GaN on SiC	Bulk GaN	SiC
	GaN on Silicon	GaN on Silicon	GaN on Sapphire
	Bulk GaN		

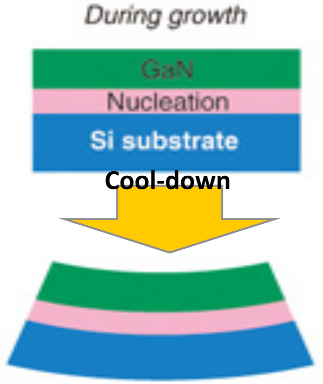
What Makes GaN on Silicon EPI Growth Difficult

1) 17% Lattice mismatch between GaN and Si → High defect density
2) 54% Thermal mismatch (CTE) → Material cracks upon cooling
3) Meltback etching → 3D defects causing poor yield



Si SiC

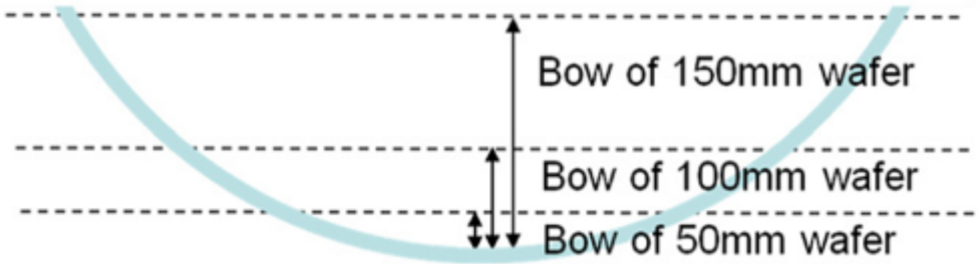
1

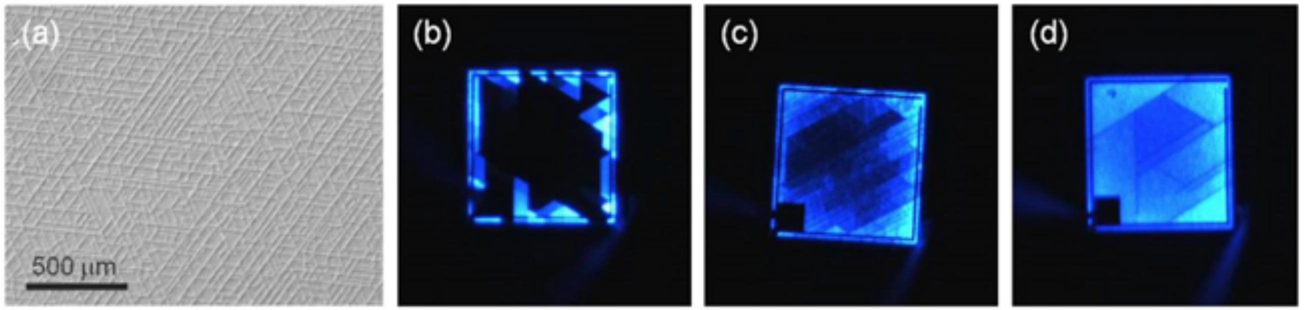


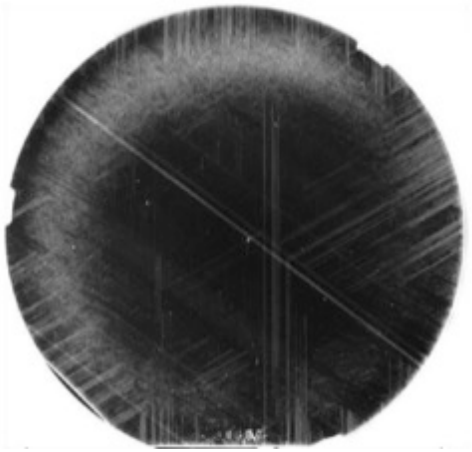
GaN under tensile stress after cooldown

2

- Wafer bow and the potential for cracking must be controlled



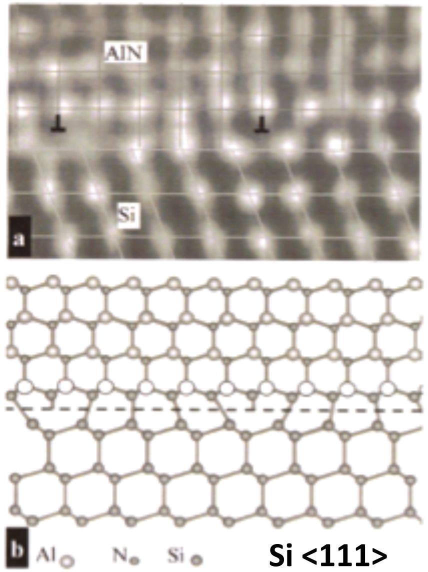


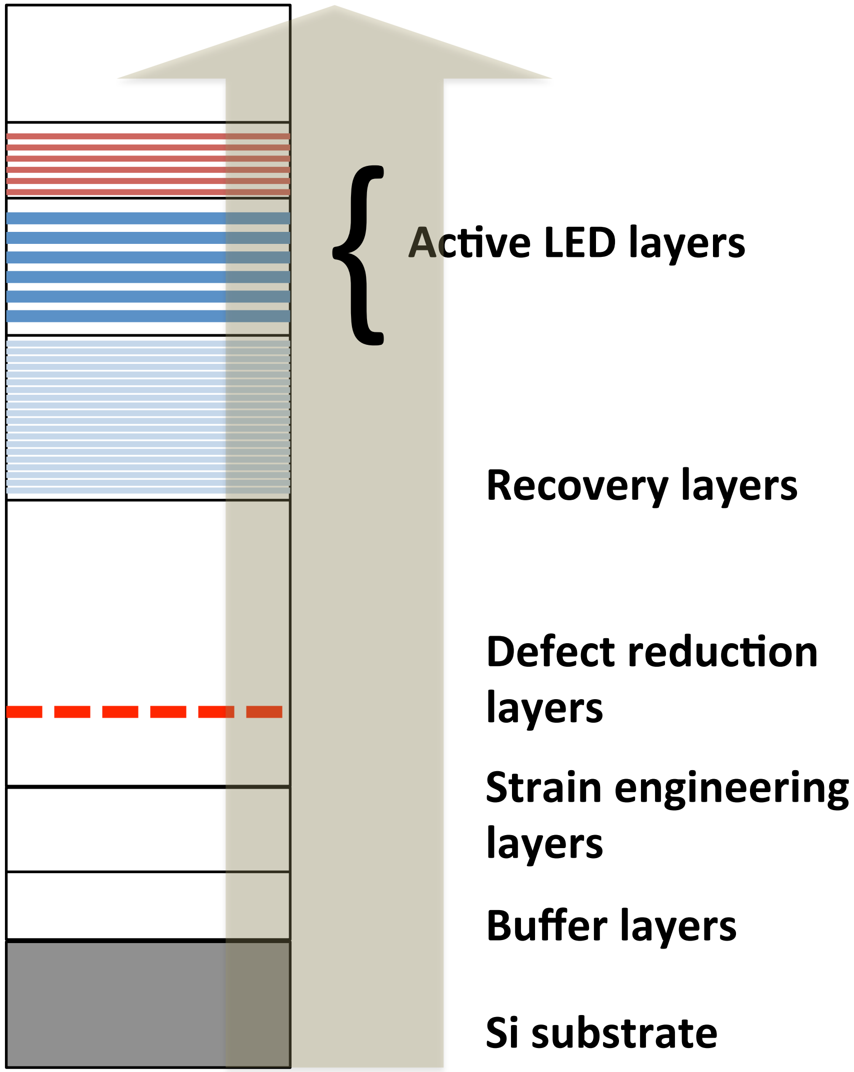


3

How to Tackle the Challenge

- **Thermal mismatch**
  - Strain engineering layers enables (0±10)um bow upon cool down
- **Lattice mismatch**
  - Recovery layers, defect reduction layers as well as strain engineering layers enable good material quality
- **Melt-back**
  - Special treatment of the substrate surface as well as buffer layers eliminate the melt-back effect – if not countered leads to poor GaN surface
- **Plessey has IP and the know-how in EPI growth to overcome these issues**



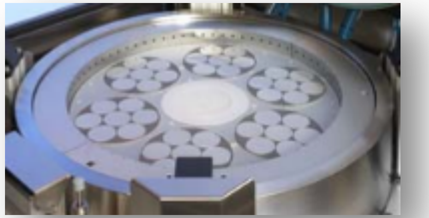


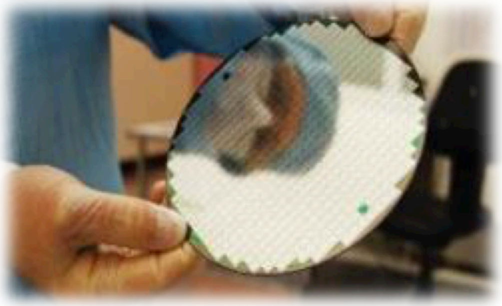
Acquired GaN-on-silicon technology from University of Cambridge (CamGaN)

UNIVERSITY OF CAMBRIDGE

GaN on Silicon

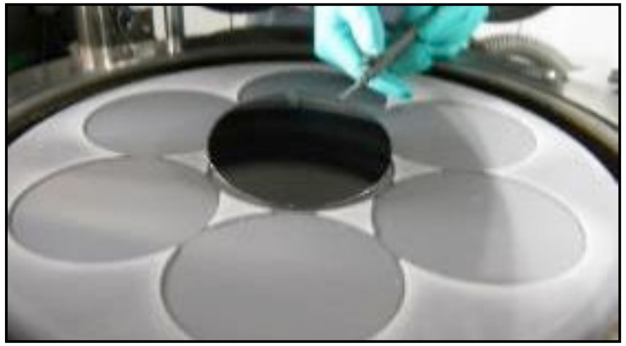
- GaN methodology limited by ability to grow crystal epitaxy on silicon substrate via MOCVD (metalorganic chemical vapour deposition)
- Strong combination of
  - Cambridge epitaxy technology (>15 years)
  - Plessey's semiconductor development and manufacturing expertise
- Base material for producing high performance blue LEDs
  - Primary pump for SSL – General illumination





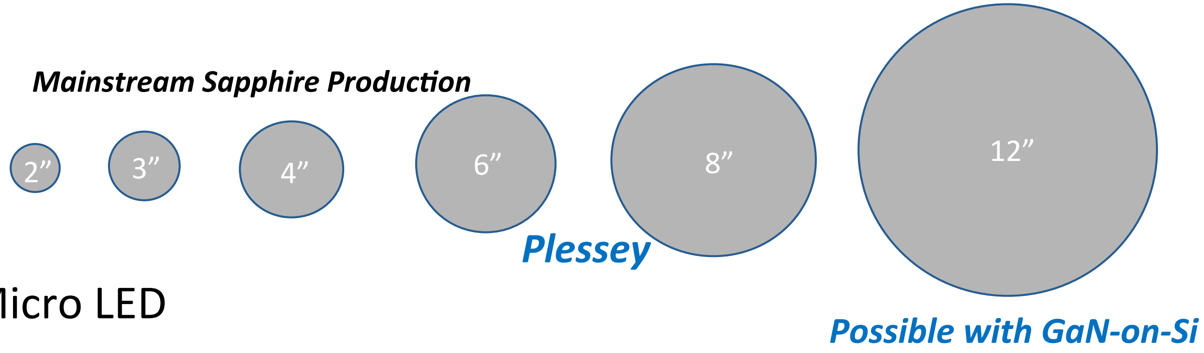
Wafer Size

- Incumbent LED technologies typical use 4" silicon carbide (SiC) or sapphire substrates, which are expensive and difficult to scale-up to 6" wafers and beyond
- 6" wafers produce c.15,000 1W ($1mm^2$) LED/s wafer
- Plessey benefits from a rare combination of a 6" semiconductor line and GaN-on-silicon capability



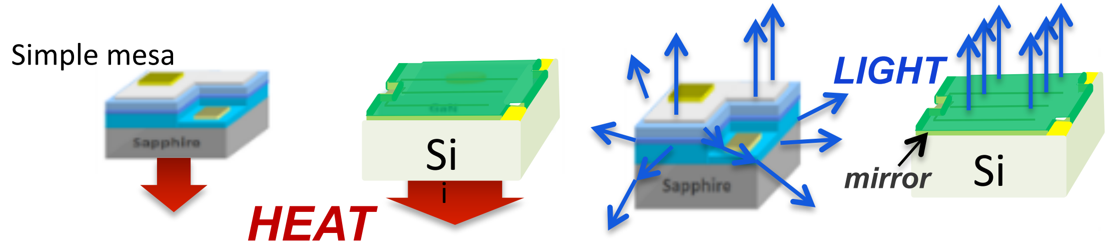
GaN-on-Si Value Proposition

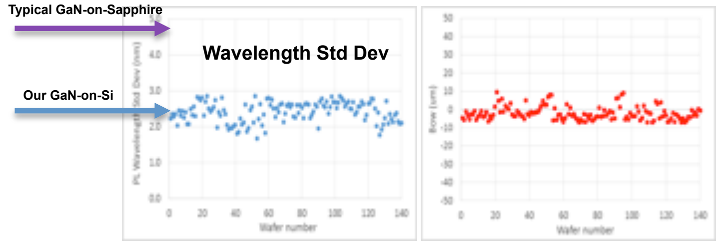
- Cost saving and scale up using large wafer diameters and silicon fab capabilities



- Large wafers enable larger die and integration
  - Power LEDs, Smart lighting / Integration, Power deices, Micro LED

- Exploit other inherent features to provide application advantages
  - Thermal properties
  - Surface emission
  - Uniformity



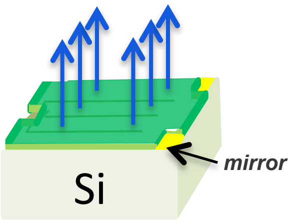


High levels of integration and micro scale semiconductor processing capability

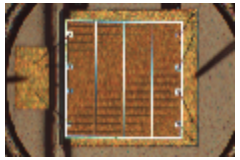
- **Cost effective high power LEDs**
- **Embedded electronics – smart devices (IOT)**
- **Micro LEDs – Addressable arrays**

Technology Roadmap

APPLICATION BENEFITS



- **Cost Reduction by Scaling to 8” Si**
- **Large Area LEDs**
- **Surface Emission**
- **Superior Thermal Performance**
- **Competitive performance**



Hi-Voltage (>48V) DC / AC LEDs for system level benefits in
- Retrofits (space constraint)
- Driver efficiency
- Automotive

High Density LED Arrays for
- Automotive Headlamps
- Intelligent LED Displays
- Power Projection Sources

- **White light beam shaping**
- **Reduced secondary optics**
  - Size and format
  - System cost advantages
  - Greater design freedom
  - Spots
  - Hi Bays
  - Stadiums

- **Chip Direct Packaging**
  - High Reliability (no bond wires)
  - Best thermal capability
  - Integrate with array modules

- **CSP / WLP**
  - Flat Top for Direct Optical Attach
  - Optimized Active Area Usage
  - No Far Field Wire Bond Shadow
  - Low Contact Resistance
  - Low cost

- **On-Chip Diagnostics & Controls for**
  - Temperature
  - Intensity
  - Spectrum
  - ESD
- **Connectivity & Communications**
- Micro displays

n-up VLED Chip on Si

HV Segmentation

- **VHA process**
- **Segmented LED on chip**

Chip Scale Optics and Reflectors

- On Chip white light
- Collimation potential down to 10 degrees
- ***Orion***^{TM} **Module series**

Advanced Packaging

- **Chip Direct Packaging (CDP)**

TODAY

CSP / Wafer Level Packaging

- Mount on Silicon
- n-Up VLED with wire bond
- Two bottom contact
- Wafer level phosphor dispense
- TSV-Through Silicon Vias
- Wafer scale LED to sub-mount

Intelligent LED
Monolithic Si-Integration

- Double bottom contacts
- Active bonded wafer
  - Addressable arrays
  - Zener Diode
  - Low Power regulation
  - Photodiodes

KEY ENABLING TECHNOLOGIES

GEN 1: Vertical LED	GEN 2: Segmentation/ Chip Scale Optics and Advanced Packaging	GEN 3: Wafer Scale Packaging &TSV	GEN 4: Active Sub-mount

GaN on Silicon Platform

Technology Platform

Plessey GaN on Silicon Platform

- MOCVD based interface technology - matching single crystal silicon in wafer form to single crystal GaN
- Developed following over 10 years research at University of Cambridge
- IP protected through granted patents and know-how

- GaN semiconductor fabrication / processing line capable of processing GaN into electronic devices
- 24/7 operation enabling reduced cycle times / fast development / IYM for production release
- Silicon and GaN Semiconductor engineering skills

Enabled Technology Streams

High Brightness LEDs	Micro LEDs	Power Devices	UV LEDs	Photonic Integration	Advanced Sensors

Market Segments

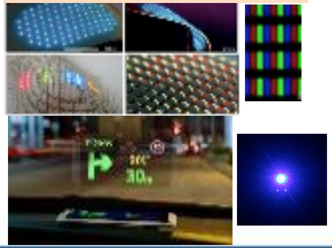
Solid State Lighting
- Power LEDs
- Spot lighting
- Down lights
- High Bays
- Flood lighting
- Horticulture

Consumer Displays
- Watch
- AR / VR

Industrial Arrays
- Direct printing
- 3D printing

Wearables

Medical



Automotive
- Electric vehicals
- Power train
- Control

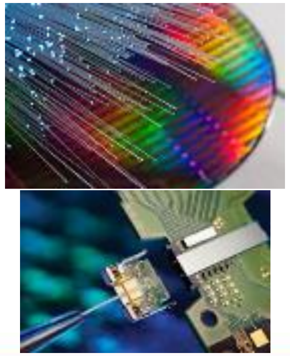
Telecom
- High freq switching

Industrial / Space
- Power switching
- Power amps

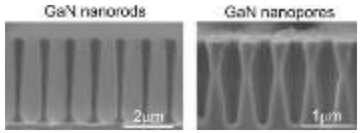
Medical
- Dental curing
- Sterilization

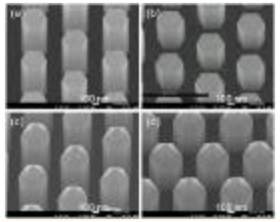
Industrial
- Curing

Telecom
- Advanced data handling – ultra high speed



Nano scale sensors:
Industrial
Medical





Possible Applications for Micro LED Arrays / Displays

Outdoor Wearable Display

Head Mounted Display (AR/VR)

Head Up Display

Micro/Pico Projector

Smart Phones and Watches

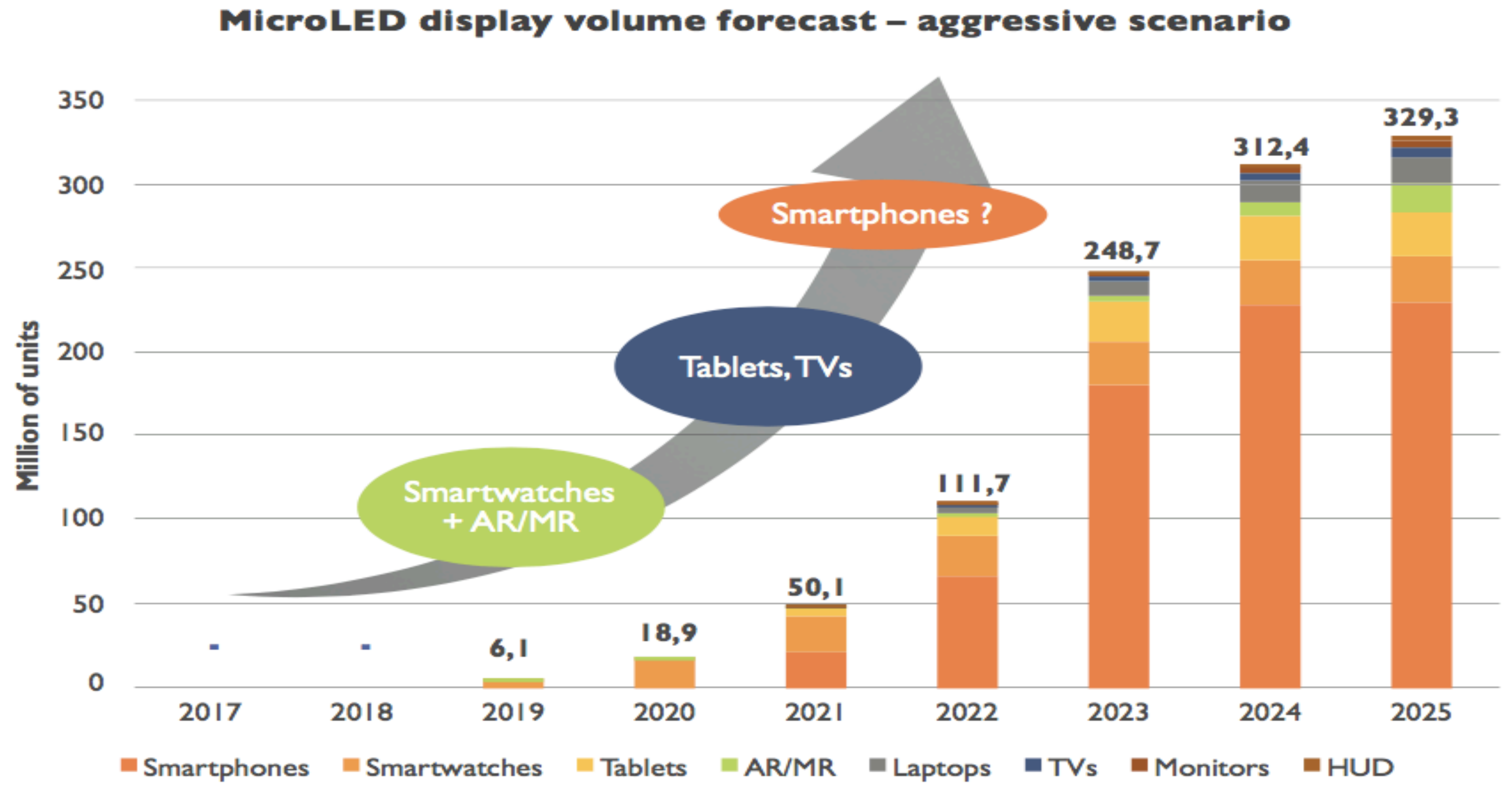
Pretty much all the smart phone and smart watch displays fail under intense direct sun light

* Images from internet

* Images from internet

Smart gadgets are smart, but not too “bright” !

Market Forecast



(Yole Développement, February 2017)

Evolution of VR/AR Headset

Goal is an Imperceptible Near Eye Display (NED)

Qualcomm Mixed Reality Report – March 2017

Major and Emerging Headset Players

Qualcomm – *SnapdragonVR*

Samsung – *GEAR VR*

LG - VR

Sony – *PlayStation VR*

Oculus - *Rift* (Facebook)

HTC - *VIVE*

Microsoft – *HoloLens*

Amazon - Lab126

Google - *Glass* (next gen!)

ODG

Microsoft HoloLens

AVEGANT

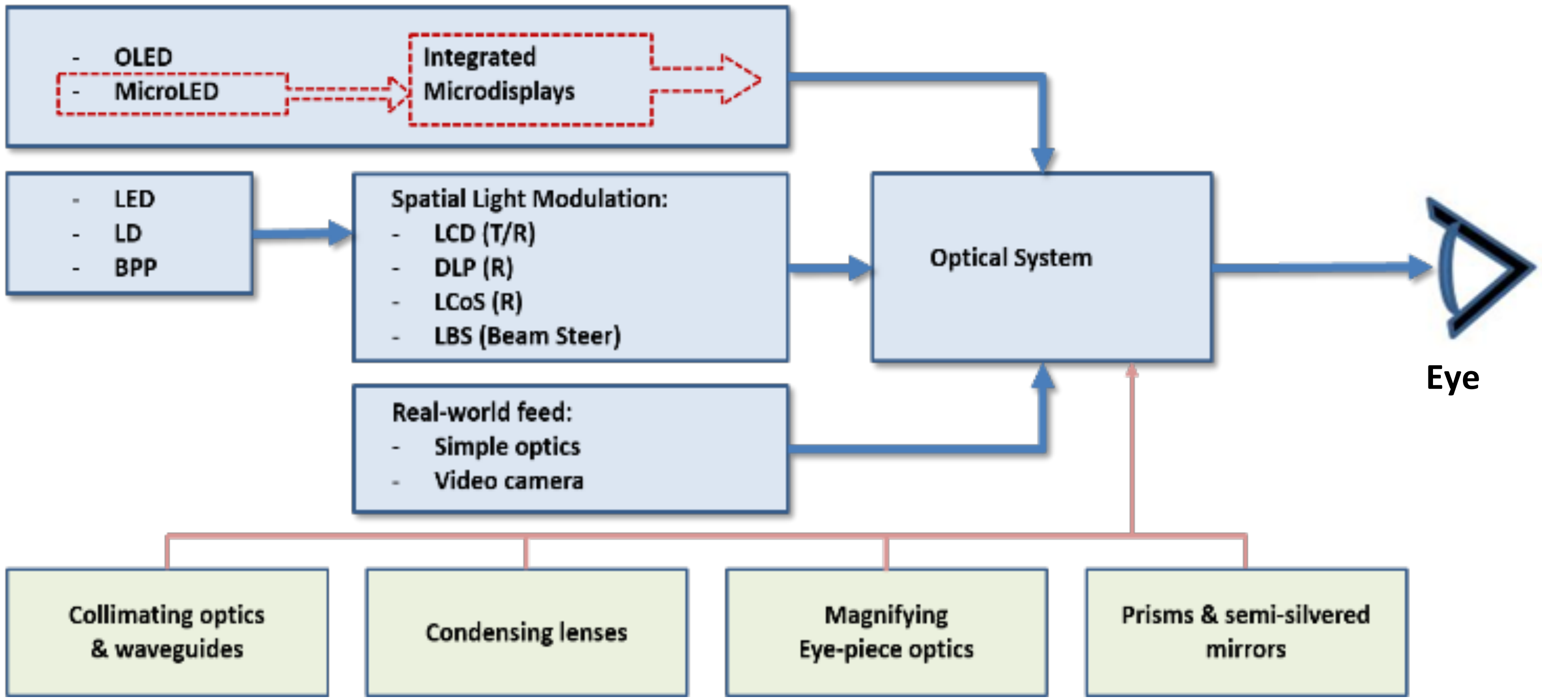
Avegant - raised $48.6M from Intel Capital, competed Series C round additional $13.7 million April 2017.

ODG announced $58M Series A. Investors 21st Century Fox, Shenzhen Tech and Vanfund Jan 2017

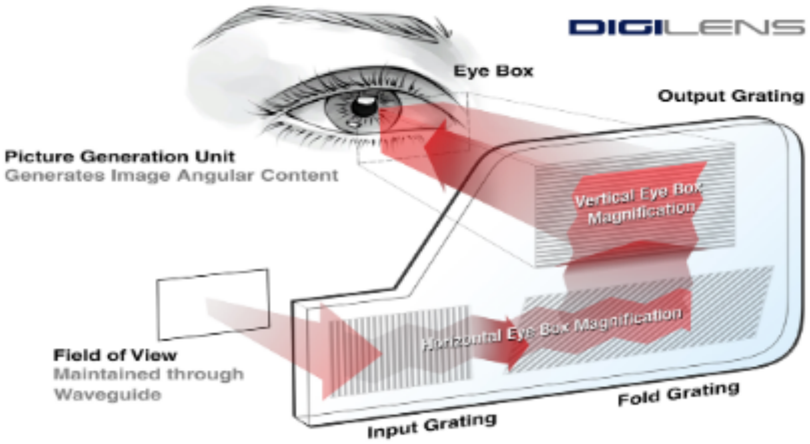
WaveOptics - $15.5M Series B July 2017

DigiLens - $22M Series B Jan 2017

Components of Near Eye Displays (NED)



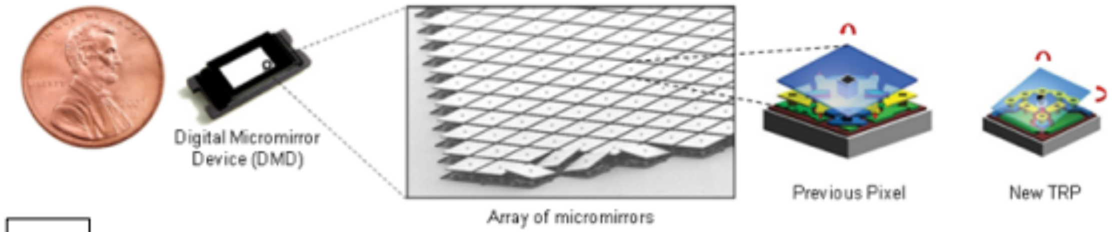
Waveguide approach



NEDs require a high-res (2000dpi+), remote positioned, colour micro-display (c. 1.5cm) with optics to form a virtual image, optionally mixed with a real-world image, in front of the eye or directly on the retina.

Digital Mirror Devices for HMD / HUD / NEDs

HMD and near-eye displays are used to create an image in the user's field of view. The display can either be see-through (augmented reality) or opaque (immersive or virtual reality).



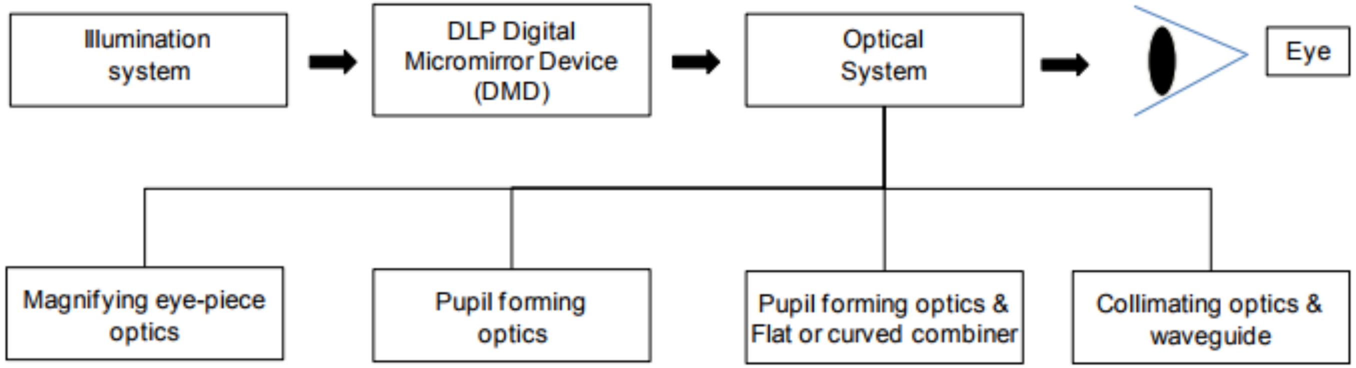
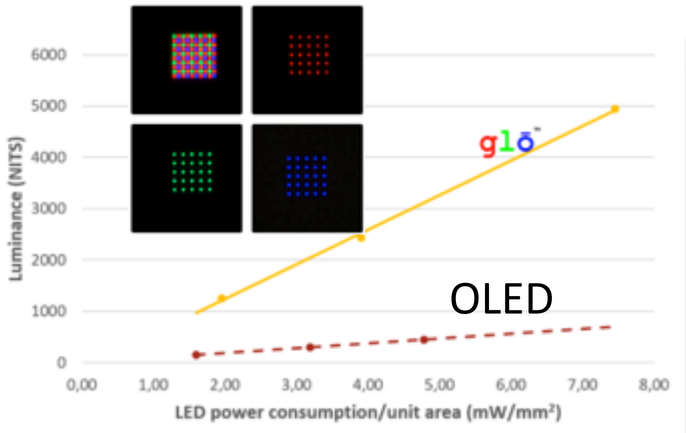


Figure 3-1. Optical System Overview

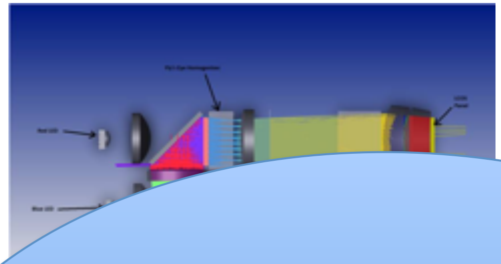
- Systems are complex
- Have significant optical losses
- Larger form factors

Micro LEDs, LCoS and OLED – Levels of Luminousity

- Nanowire µLED



- LCoS



Based on early 20µm studies – Micro LED → ~100,000 nits at 1W

~500 nits at 5mW power !

- OLED (**Data from eMagin devices)**
- **Resolution:** 800 x 600 **DSVGA**
  - **Pixel pitch:** 15µm
  - **Luminance:**
    - **XL:** 150 nits
    - **XLS:** 750-800 nits
- lution: 1920 x 1200 **WUXGA**
  - ixel pitch: 9.6µm
  - uminance:
    - **XL:** 150 nits (350mW)
    - **XLS:** 750-800 nits
    - **ULT** (engineering prototype): over 4000 nits demonstrated

~11 x 18mm

Plessey µLED - Calculations

RG

- x4 nits/W compared to glo's nanowire
- x200 nits/W compared to OLED WUXGA XL
- Similar for LCoS

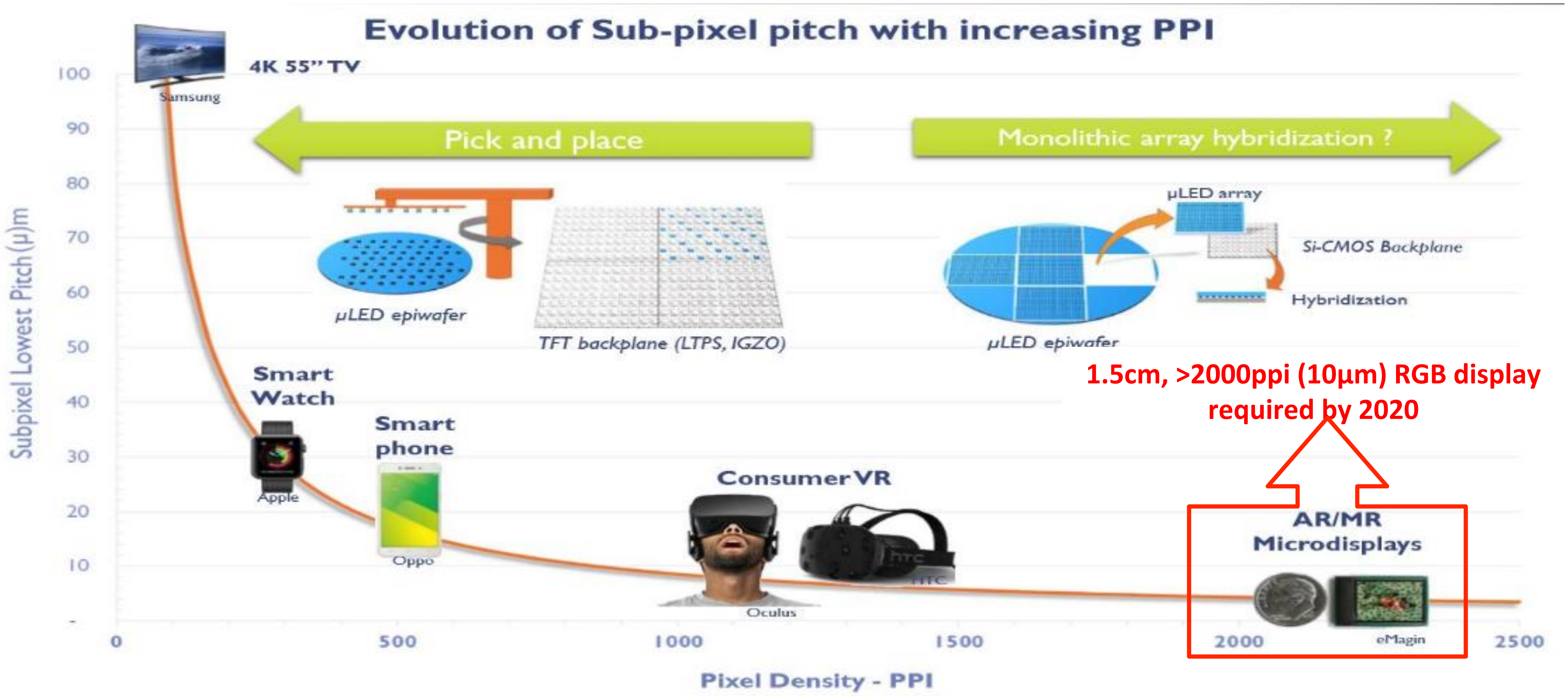
WaveOptics

- Develops Augmented Reality HUDs for consumer and business applications

WAVEOPTICS

Based in Abingdon, Oxford England
www.enhancedworld.com

Pick and Place vs Monolithic MicroLED Arrays

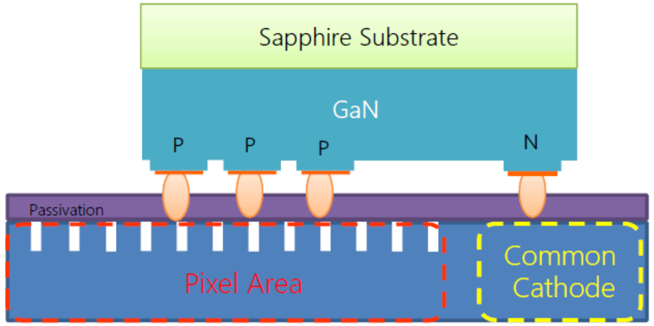


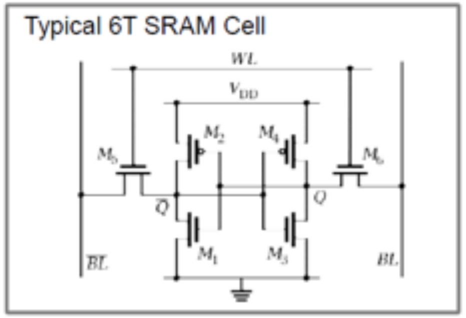
** Source: microled_displays_webcast_eric_virey_yole_development_2017.pdf*

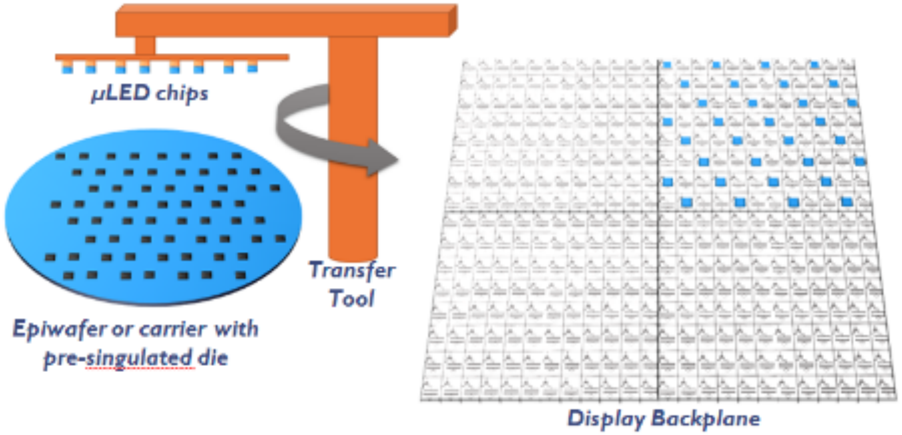
Pick and Place vs Monolithic MicroLED Arrays

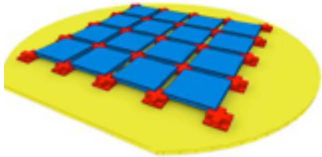
HD 720p display say 1280 x720 pixels → 921600 (>2million for 1080p)

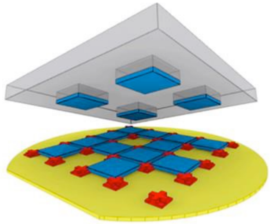
Colour requires each pixel to have RGB – would have to be direct or colour conversion layer

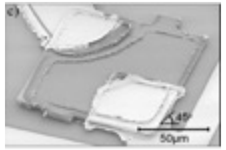


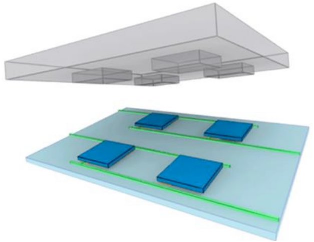


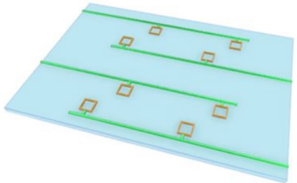


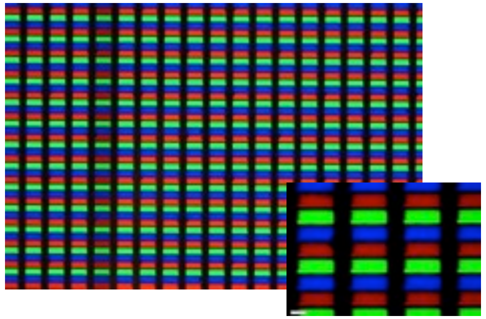












Typical smart phone 300PPI, 80µm pitch
Max brightness ~500cd/m^2 (nits)

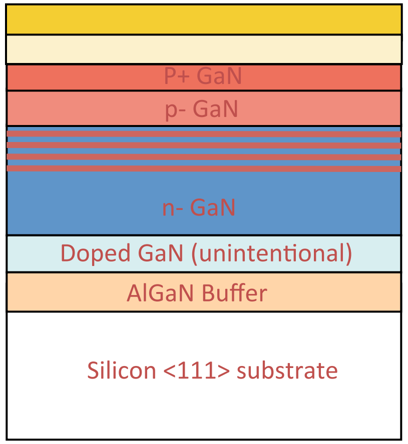
?

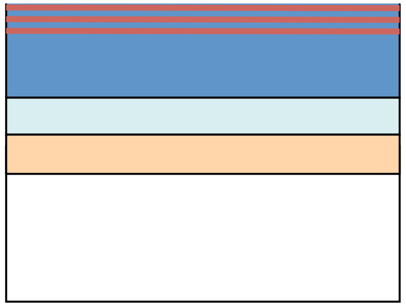
Yield

Resolution

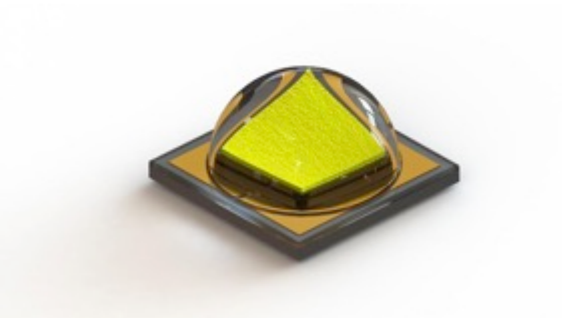
AR/VR - <10µm pixels / pitch

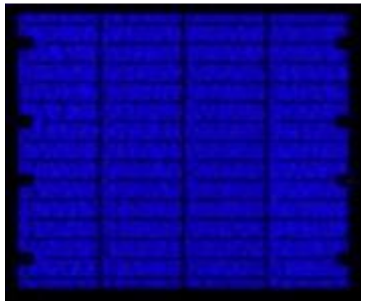
GaN on Silicon LEDs



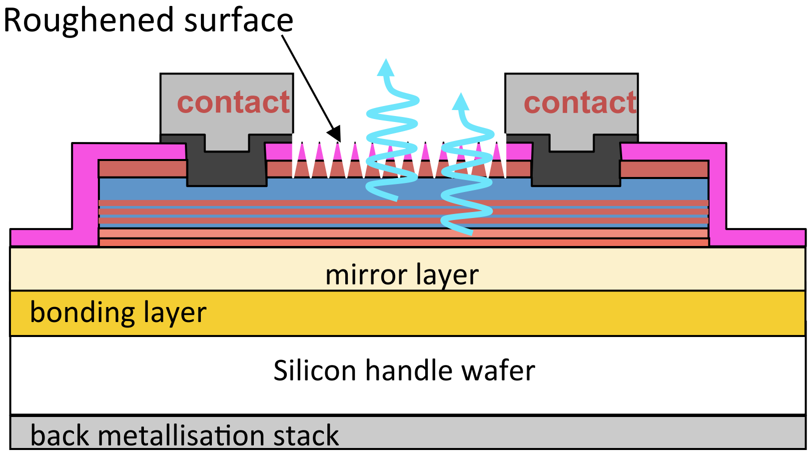


Process Vertical Device
- **Contacts**
- **Surface Roughening**

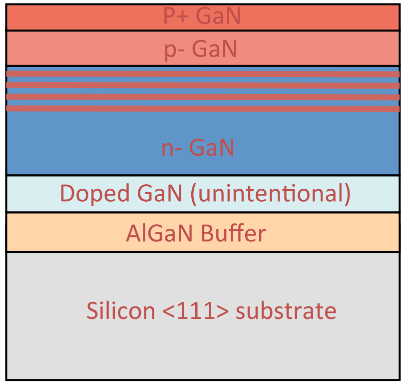


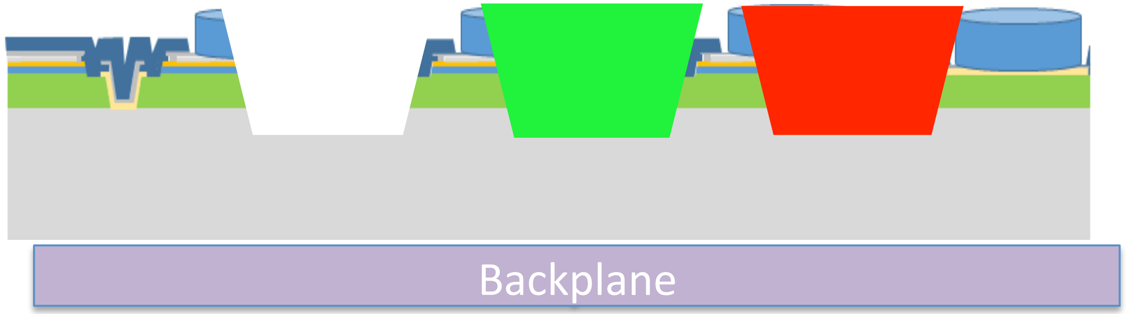


12V VHA 7070 Die
3.25 x 3.25mm



Scheme for GaN on Silicon Monolithic LED Array

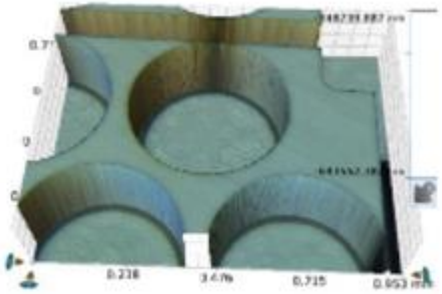




Silicon etch
- Colourization
- Cross talk

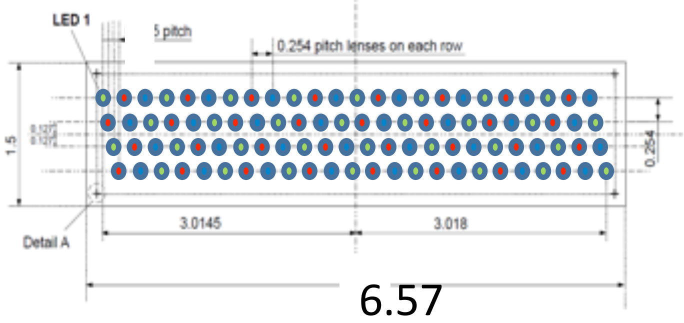
Micro LED Status and Development at Plessey

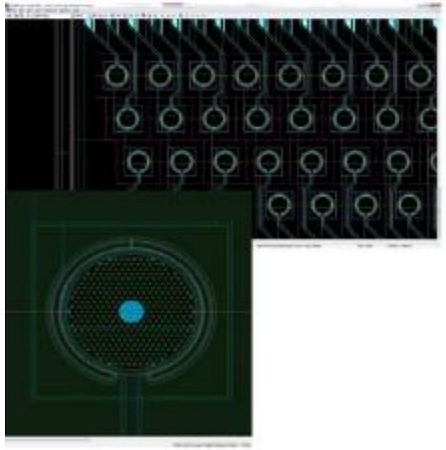
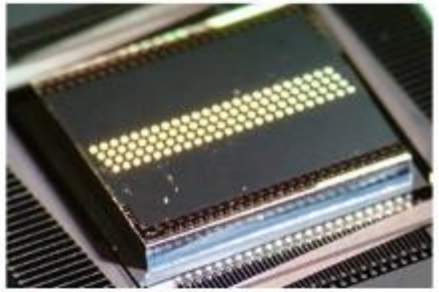
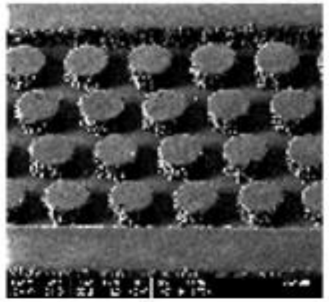
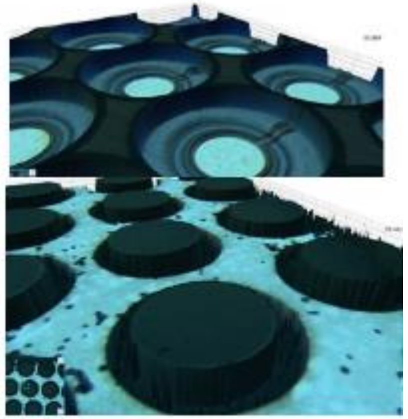
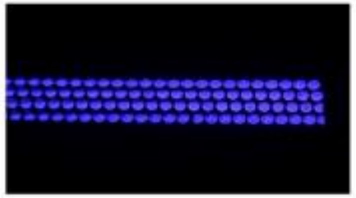
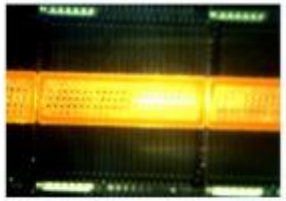
- **Early feasibility studies included:**
  - Chip scale silicon etching
    - Provide collimation off die for beam steering LEDs
    - Separation for advanced colourization
    - Prevention of cross talk
    - **Print head array applications**
    - LEDs <20μm


- **Print Head Application**
  - **20μm pixel array**
  - **On existing LED flow**
  - **RGB with phosphor**

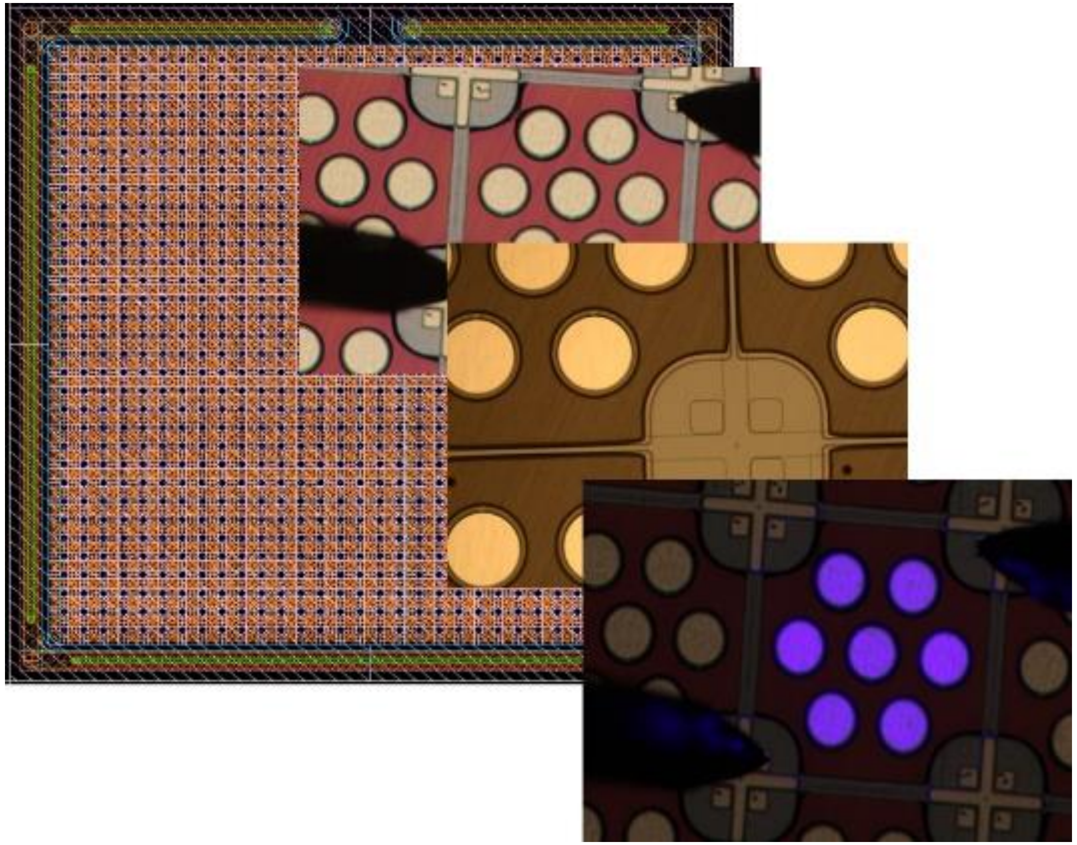
LUMEJET™
Print Technologies




Micro LED Status and Development at Plessey

- **Full RGB print head demonstrator this year**
- **Re-architecture of process for addressability to ~5μm pixels**
- **Requires studies for:**
  - Pixel size and pitch, colourization, back plane compatibility
  - In fabrication now
- **First demonstrators in Q2 2018**
- **Display Development kits Q4 2018**



- **Key Challenges**
  - LED efficiency at sub 10μm pixel sizes
  - Colourization – phosphor particle size !, Quantum dots / wells
  - Uniformity, yield and defect density
  - Micro bumping and backplane integration

In Summary

- Core technology (IP Protected) for growth of GaN on silicon, in production at 150mm and proven at 200mm
- Demonstrating standard LED performance equivalent to that of incumbent technologies
- GaN on silicon platform widely acknowledged as the only route for monolithic addressable micro LED arrays/pixels for high resolution and high luminance displays
- RGB Pixel demonstration down to 20μm
- Development underway for a range of pixel arrays down to 5μm, focusing on AR/VR applications with partners

Providing solutions for a new generation of 'wearable' / personal displays

- **High Brightness – orders of magnitude better than OLED and LCoS**
- **Low Power – providing long battery life and untethered operation**
- **Small forms factors – greater design freedom**

→ A very bright future for GaN on Silicon