Outline

> **Micro-LED Display**
  » Market Opportunity & Outlook
  » Cost Roadmap Requirements

> **Micro-LED Display Manufacturing**
  » Key Challenges
  » Mass Transfer Approaches
  » Epitaxy requirements

> **Veeco GaN MOCVD solutions**
  » EPIK Batch reactor – 6” sapphire
  » Propel single wafer reactor – 8” silicon

> **Summary**
What is Micro-LED Display?

**Goal:** scale down commercial LED signage by $10^4$ for consumer display applications (1x1mm$^2$ LED $\rightarrow$ 10x10µm$^2$ µLED)

Micro LED features miniature length less than 100 µm, smaller than a sand and mere 1% that of LED. Via massive transfer technology, µ m-level trio-color RGB Micro LEDs are moved onto substrates, creating Micro LED displays in various sizes.
Why Micro-LED Display?

Micro-LED Advantages:
- **SmartPhone**: Power Efficiency, High Brightness, Flexible/Robust
- **TV**: Higher brightness than OLED at near-LCD cost
µLED Display Shipment Forecast

- Micro LED display volume forecast –Aggressive scenario

(Source: MicroLED Displays 2017 report, February 2017, Yole Développement)

Upside µLED forecast: >300M displays by 2025

Source: Yole
Micro-LED Display Cost Targets – TV & Smartphone

**5.8” QHD Smartphone**

- Allowable LED and transfer costs (2020)
  - TV: $165; Smartphone: $11

**55” 4K TV**

- SOURCE: IHS Markit 2017, Veeco estimates
- TV: $165; Smartphone: $11
Micro-LED Display Cost Roadmap – TV & Smartphone

5.8” QHD Smartphone

- LED costs
- Transfer costs

Cost Per Display

10μm R/G/B: $60
5μm R/G/B: $30
3μm R/G/B: $10

2020 goal

<10x10μm² μLED size needed to meet TV cost target

~3x3μm² μLED size needed for smartphone

55” 4K TV

- LED costs
- Transfer costs

Cost Per Display

20μm R/G/B: $500
15μm R/G/B: $300
9μm R/G/B: $100

2020 goal

Assumptions: $400 per processed 6” Epi wafer
2μm EPI street width, interposer transfer $0.30 per field
Micro-LED Display Challenges

- High EQE \( \mu \text{LED} \) chips at \(<10 \times 10 \mu \text{m}^2\)
- Test and repair of defective pixels
- High Quality Epitaxy (defectivity, uniformity)
- Specialized drive circuitry with uniformity correction
- High yield, low cost transfer from wafer to backplane
Mass Transfer Approaches

Low to Mid Pixel density: Pick and Place

- TV
- Laptop/Tablets
- Wearable
- Smartphones
- VR

High Pixel Density: Monolithic Array Integration

- Projection micro display
- AR/AR

SOURCE: YOLE
Mass Transfer with Interposer

1. Epi Wafers (6” - 8”)
2. Interposer (8” – 12”)
3. Display

Epi field (defectivity, uniformity)
Epitaxy Defectivity and Uniformity Requirements

**Epi Wafer**
- \( \leq 1 \) Defect per Transfer field
  - \(~1 \text{ cm}^2\) for 6” wafer
- 1 - 2nm wavelength range
  - (within transfer field)

**Interposer**
- \( \leq 1 \) Defect per Donor field
  - (Phone: \(~1 \text{ cm}^2\))
  - (TV: \(~10 \text{ cm}^2\))
- 1 - 2nm wavelength range

**Display**
- \( \leq 1 \) Defect per Color
- 1 - 2nm wavelength range
  - (before correction)

Epitaxy specifications are calculated at transfer field level
Veeco MOCVD… *Cleanest* Production Technology

**Veeco TurboDisc™ Technology**
- Uniform deposition by design
- Wide process window
- **Low defectivity:** < 1 / cm$^2$
- Longest run campaigns
- Ultimate process repeatability

**EPIK™ 700**
- High capacity Batch Reactor for 6” sapphire (28x6”)

**Propel™**
- Single Wafer Reactor for 8” Si or sapphire

**K475i™**
- Batch Reactor: 7x6” GaAs
Veeco EPIK – Defectivity yield for smartphone
3x3μm² μLED → 1μm killer defect size

Display assumptions:
- QHD resolution (2,560 x 1,440)
- 3x3μm² LED size
- 2μm street width
→ 0.92 cm² Epi donor field per color

CS920: ≥ 0.8 μm defects

94% Yield (62 of 66 Fields)
Veeco EPIK - Defectivity yield for TV

$9 \times 9 \mu m^2 \mu LED \rightarrow 3\mu m$ killer defect size

Display assumptions:
- 4K2K resolution (3,820 x 2,160)
- $9 \times 9 \mu m^2$ LED size
- $2\mu m$ street width
→ $10 \ cm^2$ Epi donor field per color

93% Yield (13 of 14 Fields)

CS920:
$\geq 3 \ \mu m$ defects

≤ 1 Defect  >1 Defect
Veeco EPIK can achieve >80% uniformity yield for μLED Display
Veeco Propel can achieve >80% uniformity yield for μLED Display
Impact of Wavelength uniformity requirement
5.8” QHD Smartphone

Assumptions:
- 3x3um² LED; EPIK 14x6"; Epi wafer cost $400; $0.30 transfer cost per field; interposer transfer field 5x5cm²

- $11 cost target (LED + transfer) for μLED smartphone is achievable
  - Optimal Epi transfer field → 7x7mm² to 8x8mm²

$11 cost target (LED + transfer) for μLED smartphone is achievable
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Impact of Wavelength uniformity requirement

55” 4K TV

- $165 cost target (LED + transfer) for μLED TV is achievable
  - Optimal Epi transfer field → 7x7mm² to 11x11mm²

Assumptions: 9x9um² LED; EPIK 14x6”; Epi wafer cost $400; $0.30 transfer cost per field; interposer transfer field 5x5cm²
Summary & Conclusions

> Micro-LED Display has significant advantages over LCD & OLED
  » Brightness & efficiency (smartphone)
  » Higher brightness than OLED and near-LCD cost (TV)

> Small LED size with high EQE is key to enable consumer applications
  » ~3x3µm² for smartphone; ~10x10µm² for TV

> Epitaxy requirements (for mass transfer with interposer)
  » Defectivity: ≤1 per Epi donor field (1 – 10 cm²)
  » Uniformity: 1-2 nm range over Epi transfer field (0.5 – 1 cm²)

> Veeco’s MOCVD solutions meet cost and yield requirements for µLED smartphone and TV
  » EPIK for 6” sapphire; Propel for 8” silicon