Market Leading Wide Color Gamut, Narrow-Band Phosphors by GE & Path Towards Enabling Next Generation Displays

2023 Color Conversion MicroLED Association Webinar: March 6, 2023

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1. Traditional white emitting WCG pc-LED:
   - Full scale production since 2014
   - >60 billion commercialized KSF LEDs
   - In fast response time full array local dimming displays

2. Narrow Band Green Phosphors:
   - brightness/QE comparable to B-SiAlON
   - Enables 88% rec. 2020 on chip solution with KSF
   - Currently sampling partners

3. Back lit/Minileds:
   A. Remote parts: small size KSF phosphor + green phosphor = commercialized in 2020
   B. Magenta LEDs: KSF on chip + QD film architecture = commercialization in 2021

4. Microleds:
   - Submicron size KSF development
   - inks/printing/prototypes = collaboration

IJP KSF

KSF phosphor on blue LED

“Magenta” LED package for display
License from GE required for use in display with LED source
- Enables wide color gamut – excellent match to DCI-P3 & Rec2020 red
- On chip stability, RoHS compliant with high efficiency
- Continued small-size innovation for next-generation form factors
- GE and Current Lighting Solutions partner for the licensing, manufacturing, sales, and advancement of PFS/KSF TriGain(TM) Technology.

>60 Billion LEDs containing KSF sold into the display industry since 2014

19 Licensees
6 Countries
4 All major display sectors (TV, laptop/monitor, tablet, mobile)

“Although there has been lots of talk about QD and OLEDs, there has been a real revolution in phosphors”
- Display Daily 2020

“KSF phosphor is the unsung hero of WCG + HDR”
- Hendy Consulting, 2020

“In just 3 years PFS has gained rapid acceptance in displays where it is now the leading red material for Wide Color Gamut (WCG) LCD BLUs”
- Yole Report 2017

KSF Phosphor Technology Licensing Global Presence

$K_2SiF_6:Mn^{4+}$ (PFS/KSF)

Narrow-band red emission centered at 631nm (5 peaks <2nm FWHM)
PFS/KSF is implemented across all display sectors

- Samsung, Apple, Huawei, LG, BLU, Razer, Red, Nokia, Sonim
- HP, Lenovo, Dell, Asus, Apple, Microsoft, Razer, MSI, Samsung, LC MSI, Samsung, LG
- Apple, Samsung, Lenovo, Huawei, Microsoft, Asus
- Samsung, LG, Sony, Vizio, TCL, Hisense, Toshiba, Insignia, Sharp

- Ultra-rugged
- 2D backlit monitors/laptops
- Gaming Laptops: 300 Hz refresh rate
- FALD 4K HDR TVs
- DCI P3 > 96%

KSF commercialized in on-chip & remote film + miniled architectures

*Partial list – GE investigation – Not exhaustive*
<table>
<thead>
<tr>
<th>Application</th>
<th>High Efficacy Lighting</th>
<th>WCG Display edge lit</th>
<th>WCG Display direct lit</th>
<th>WCG Display micro-LED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Implementation</td>
<td>On LED (~3 mm)</td>
<td>On LED (~1 mm)</td>
<td>On mini-LED (~100 um) or remote film</td>
<td>On µLED with longer pathlength (inks)</td>
</tr>
<tr>
<td>Commercial Status</td>
<td>Commercialized 2014</td>
<td>Commercialized 2014 (&gt;60 billion LEDs)</td>
<td>Commercialized 2020</td>
<td>Sampling</td>
</tr>
<tr>
<td>Product Example</td>
<td><img src="https://example.com/image1" alt="Image" /></td>
<td><img src="https://example.com/image2" alt="Image" /></td>
<td><img src="https://example.com/image3" alt="Image" /></td>
<td><img src="https://example.com/image4" alt="Image" /></td>
</tr>
<tr>
<td>Avg Particle Size</td>
<td>25-30 um</td>
<td>15-20 um</td>
<td>3-9 um</td>
<td>Sub-micron</td>
</tr>
<tr>
<td>Nano-KSF</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Microscopy</td>
<td><img src="https://example.com/image5" alt="Image" /></td>
<td><img src="https://example.com/image6" alt="Image" /></td>
<td><img src="https://example.com/image7" alt="Image" /></td>
<td><img src="https://example.com/image8" alt="Image" /></td>
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Decreasing particle size to meet display industry needs
**Narrow Band Phosphor Innovation by GE**

Successful commercialization for on-chip & miniLED remote films, working towards commercialization for microLED

<table>
<thead>
<tr>
<th>GE Phosphor Portfolio</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 KSF for LED package (“on chip”)</td>
<td>Commercialized since 2014 (&gt;60 billion high brightness WCG LED packages)</td>
</tr>
<tr>
<td>2 Small size KSF for films/minileds</td>
<td>Commercialized in tablets, monitors, laptops since 2021</td>
</tr>
<tr>
<td><strong>Under Development at GE Research: Sampling Customers</strong></td>
<td></td>
</tr>
<tr>
<td>3 KSF inks (color filter/microleds)</td>
<td>Providing submicron powder, inks &amp; printed parts to select partners</td>
</tr>
<tr>
<td>4 Alternate Mn⁴⁺ Red</td>
<td>30% faster response time vs. KSF (full array local dimming/films), small size</td>
</tr>
<tr>
<td>5 Narrow Band Green</td>
<td>Improved color gamut vs. B SiAlON</td>
</tr>
<tr>
<td>6 High nit Eu³⁺ red</td>
<td>618 nm peak emission for improved brightness: Lighting &amp; Displays, 1.8 ms tau</td>
</tr>
</tbody>
</table>

1. **Alternate Mn⁴⁺ Red**
   - Improved thermal properties & fast response
   - Available in small size

5. **High nit red film**
GE Research: Vertical Integration & Collaboration to Create the µLED Value Chain

µLED partners

Phosphor converted parts/microLED Arrays

Collaboration:
- µLEDs
- Inks/binders
- Printing/films

Films/Printing

Phosphor Inks

Phosphor powder

GE LED Phosphors: Murphy MicroLED Association 2023
GE KSF Inks/Ink Jet Printing for microled color conversion

- R, G, B MicroLED architecture “red gap” issue vs. B microLED + color conversion
- pc-MicroLEDs: Potential for improved energy efficiency, color quality, contrast & form factor

- GE Patented technology enables small size, high absorption KSF
- Inks: Submicron particle size with high quantum efficiency
- Customer sampling is underway.
- Contact us to learn more: murphyj@ge.com

Submicron KSF in an ink
Air stable/no encapsulant
GE monogram = 25 mm diameter
GE ink jet printing submicron KSF for microled displays

Video by Kevin Shoemaker
KSF narrow band red phosphor: Reliable, Bright & best color gamut

KSF has better reliability

KSF phosphor can be an on chip solution because it has better reliability to air, humidity, temperature & blue flux.

KSF has better red color

KSF phosphor shows more narrow red emission than commercialized red QDs enabling higher quality red color (wider color gamut)

KSF has better brightness (QE)

- KSF phosphor shows no self absorption & will not absorb green or red emission.
- InP QDs absorb blue well, but absorb throughout the visible, resulting in a decrease in EQE in thicker dense films, absorption of green emission & unintentional excitation from ambient room light.

GE LED Phosphors: Murphy MicroLED Association 2023
KSF vs. InP QDs for MicroLED

KSF wider color gamut, better reliability & no self-absorption

KSF Phosphor Improvements in 2022:
1. Synthesis: smaller size, higher %Mn, minimizing defects to improve IQE & 450nm Absorbance.
2. Surface chemistry: reduced agglomeration/better dispersion.
3. Ink & film deposition/printing optimization

%EQE = \frac{\text{red photons emitted from film}}{\text{incident blue photons}} \sim [450\text{nm Absorbance} \times \text{Internal QE} \times (1 - \text{self absorption loss})]

Advantage QDs
Advantage KSF
Advantage KSF (no self absorption)

GE Patented technology enables small size, high absorption KSF
pc-µLED architectures with reduced cross talk, higher light conversion efficiency

(pc-µLED = phosphor converted micro-LED)

Architectures that use “thicker” color conversion layers, target d65 color point or recycle blue light will show most benefit in reliability, color gamut & brightness using KSF phosphor.

GE LED Phosphors: Murphy MicroLED Association 2023
Examples of architectures using combination of down-converters

Properties that can be enhanced by combining down-converters

- Color
- Brightness
- Efficiency
- Uniformity
- Response time
- Cost
- Marketability

1. QD Film + phosphor
   - Phosphor patterned on back reflector

2. QD Film + phosphor
   - Phosphor under LED lens

3. KSF + Nitride + Green phosphor
   - KSF + Nitride red phosphor on chip

4. KSF + Green phosphor
   - KSF in remote part (film)

5. KSF + green QD
   - KSF + Perovskite

6. KSF + red phosphor + QD part
   - Two phosphors on chip + remote QD part
Example 6 – Narrow-band phosphors and QDs in harmony

Unique combination of down-converters including:

**KSF Red, Green Phosphor (on chip)**

**QD red and green (remote part)**

LED spectra

QD part spectra

Front of screen spectra

GE LED Phosphors: Murphy MicroLED Association 2023
**Summary of Small Size GE KSF vs. QDs**

<table>
<thead>
<tr>
<th>Property</th>
<th>KSF phosphor</th>
<th>Red InP QD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Color gamut</td>
<td>5 peaks &lt;2nm each</td>
<td>FWHM &gt;38nm commercially</td>
</tr>
<tr>
<td>Quantum Efficiency</td>
<td>IQE &gt; 90%, EQE &gt;60%</td>
<td>EQE &lt;40% [5]</td>
</tr>
<tr>
<td>Reliability to air</td>
<td>No encapsulation necessary in commercial products</td>
<td>Encapsulation required</td>
</tr>
<tr>
<td>Reliability to moisture</td>
<td>No encapsulation necessary in commercial products</td>
<td>Encapsulation required</td>
</tr>
<tr>
<td>high temperature quenching</td>
<td>no loss at 100 °C</td>
<td>&gt;15% loss at 100 °C</td>
</tr>
<tr>
<td>High temp. curing degradation</td>
<td>&lt;2% at 150 °C for 30 min.</td>
<td>&gt;15% at 80 °C for 20 min. [6]</td>
</tr>
<tr>
<td>Reliability to high blue flux</td>
<td>Commercialized on-chip</td>
<td>Not on-chip in displays</td>
</tr>
<tr>
<td>Self-absorption loss</td>
<td>No</td>
<td>Yes, all QD colors</td>
</tr>
<tr>
<td>Scatterance</td>
<td>RI = 1.4 so provides some scattering at typical sizes</td>
<td>Must add scattering agent</td>
</tr>
<tr>
<td>Photoluminescence decay time</td>
<td>LCD like response time</td>
<td>Faster in microLED with no LCD</td>
</tr>
<tr>
<td>Absorption</td>
<td>Requires &gt;2x QD thickness</td>
<td>Higher abs. coefficient</td>
</tr>
</tbody>
</table>

- Architectures that use “thicker” color conversion films will show most benefit in reliability, color gamut & brightness with KSF vs. QD films
- Potential for hybrid KSF + QD form factors

Questions? Collaboration Interest?

- For technical inquiries please contact James Murphy: murphyj@ge.com
- For licensing inquiries contact Rachel Cassidy: rachel.cassidy1@ge.com

Summary

- KSF is the leading wide color gamut red emitting phosphor
- GE Licenses KSF phosphor for display applications
- GE Research’s focus on innovation includes:
  1. Narrow band green phosphor development
  2. Small size KSF for films & direct lit/MiniLED market
  3. Submicron KSF inks/films & printing for MicroLED market
  4. Alternative GE Red Phosphor for fast response time

Thank you for your attention & look for us at SID in May!

Exemplary Patent Assets involving PFS/KSF phosphor family
KSF Color Conversion in Direct lit/Miniled Backlights: 3 Architectures

Display Size Diversity requires LED size diversity which requires phosphor size diversity

Easiest Integration WCG Solution
Small Size KSF + green phosphor on chip

Air stability and great blue flux & thermal reliability

KSF + green in a remote part

Green can be QDs or other phosphors

- Enables high nit/best in class HDR
- high contrast ratio
- KSF remote parts now commercialized.

Widest Color Gamut Solution
Hybrid GE KSF “Magenta” LED + QD film

Green CdSe QDs = 25nm FWHM
Green Perovskite QDs < 25nm FWHM

KSF + green QD = Rec. 2020 > 91%

The color gamut of KSF on blue LEDs + perovskite QD backlight reached 95% BT.2020

Products expected in 2021

- Honglei Ji et al., SID Digest 2019, p. 1064

GE LED Phosphors: Murphy ICDT 2021
GE Narrow Band Green Phosphors

- GE is developing narrow band green phosphors to enable on chip or remote part wider color gamut displays.
- Enables 100% DCI-P3 and Adobe
- Absorbance is equivalent or higher than B-Sialon
- Good reliability: 100% HTHH (high temp./humidity) stability
- No loss in efficiency when incorporated into films

-Customer Sampling is underway.

<table>
<thead>
<tr>
<th>material</th>
<th>QE</th>
<th>Dominant</th>
<th>PL decay (µs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-Sialon</td>
<td>100</td>
<td>556</td>
<td>2</td>
</tr>
<tr>
<td>QD</td>
<td>&lt;70</td>
<td>540</td>
<td>(ns)</td>
</tr>
<tr>
<td>GE Comp 1</td>
<td>95</td>
<td>549</td>
<td>90</td>
</tr>
<tr>
<td>GE Comp 2</td>
<td>100</td>
<td>547</td>
<td>85</td>
</tr>
<tr>
<td>GE Comp 3</td>
<td>100</td>
<td>531</td>
<td>520</td>
</tr>
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GE’s new narrow band greens can hit all requirements for next generation displays
GE Alternative Red Phosphor in Development

- Emission shift towards higher energy vs. KSF is ideal for lighting applications.
- Photoluminescent decay time is about four times faster than KSF for fast response time displays.
- Absorbs more strongly than KSF.
- Blending with KSF for display: Tradeoff of improved response time and less phosphor loading for color gamut.
- Optimization in progress.
- Customer sampling in Q3 2022.
Structures Requiring A Display License to GE PFS/KSF Patents

**On-chip Configuration**
- PFS/KSF + Green phosphor in blue LED package

**Magenta LED Configuration**
- KSF on blue LED
- KSF on blue LED with Green Remote Part
- "Magenta" LED or miniLED Array

**Remote Part Configuration**
- Remote KSF sheet/film for display

**microLED Configuration**
- KSF on blue microLED as red sub-pixel
- PFS/KSF converts blue microLED to red sub-pixel

**Narrow emission** (5 peaks <2nm FWHM) centered at 631 nm

\[ \text{K}_2\text{SiF}_6:\text{Mn}^{4+} \] (PFS/KSF)

Cassidy & Murphy, SID Display Week Business Conference, 2022