

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

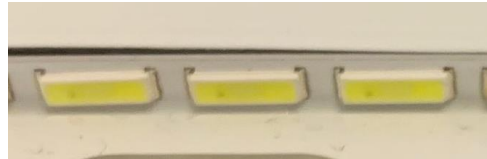


2023 Color Conversion MicroLED Association Webinar: March 6, 2023

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**GE Research (Niskayuna, NY)**

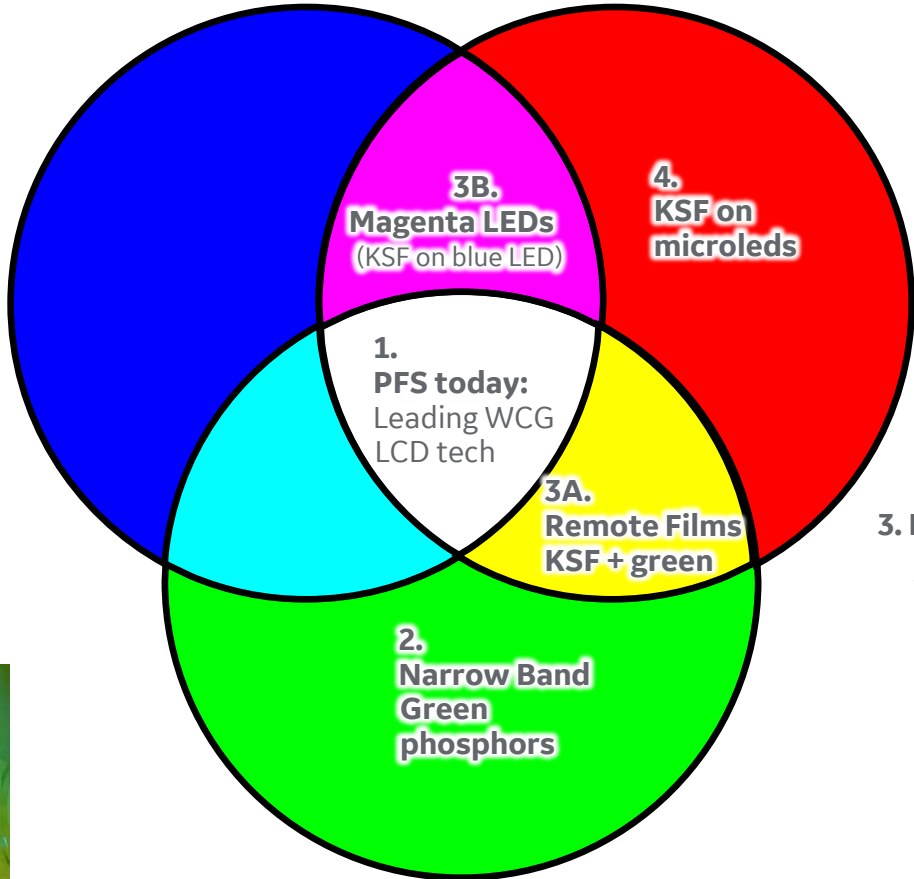
## 1. Traditional white emitting WCG pc-LED:

- Full scale production since 2014
- >60 billion commercialized KSF LEDs
- In fast response time full array local dimming displays



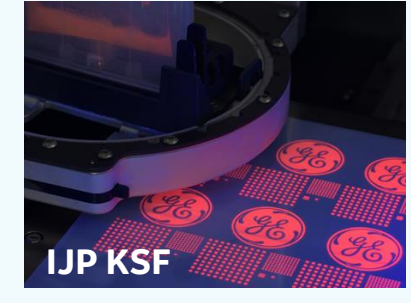
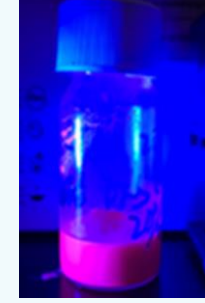
## 2. Narrow Band Green Phosphors:

- brightness/QE comparable to B-SiAlON
- Enables 88% rec. 2020 on chip solution with KSF
- Currently sampling partners



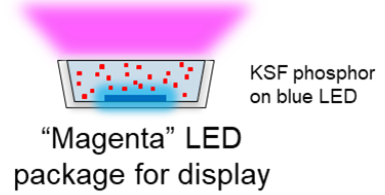
## 4. Microleds:

- **Submicron size KSF development**
- **inks/printing/prototypes = collaboration**

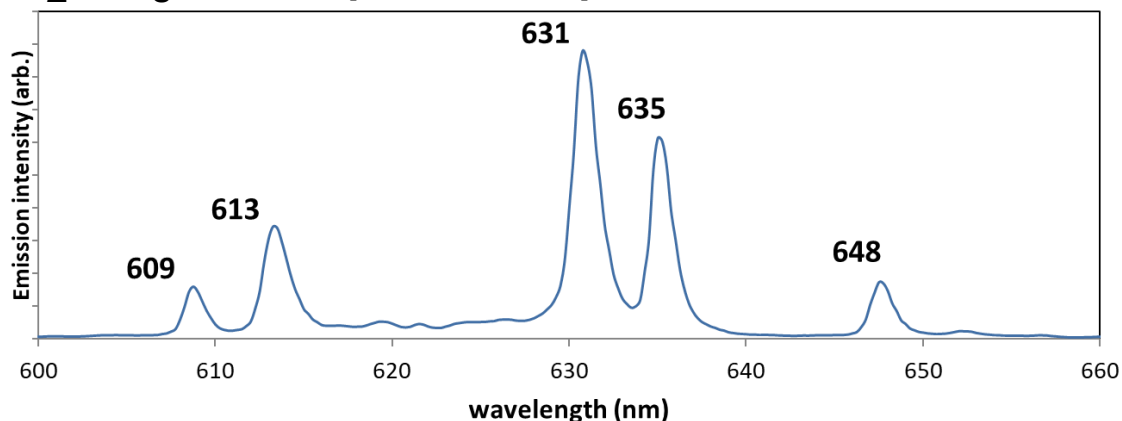
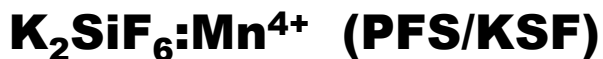


## 3. Back lit/Minileds:

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



# KSF Phosphor Technology Licensing Global Presence



Narrow-band red emission centered at 631nm (5 peaks <2nm FWHM)

- 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.

***“It’s no secret that this high-performing phosphor has been a challenge for QDs to compete with”***

– 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

**>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

# PFS/KSF is implemented across all display sectors



Created by Jamison Weser from Noun Project

**Samsung, Apple, Huawei, LG, BLU, Razer, Red, Nokia, Sonim**



- Ultra-rugged

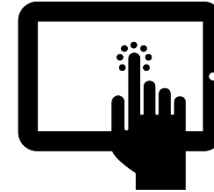


Created by Guilherme Silva Soares from Noun Project

**HP, Lenovo, Dell, Asus, Apple, Microsoft, Razer, MSI, Samsung, LC MSI, Samsung, LG**

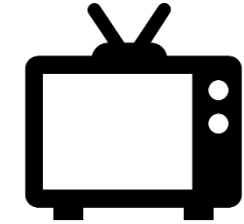
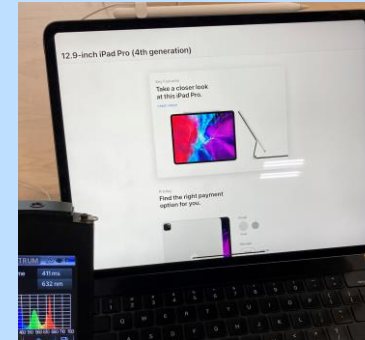


- 2D backlit monitors/laptops
- Gaming Laptops: 300 Hz refresh rate



Created by Luis Prado from Noun Project

**Apple, Samsung, Lenovo, Huawei, Microsoft, Asus**



Created by Creative Stall from Noun Project

**Samsung, LG, Sony, Vizio, TCL, Hisense, Toshiba, Insignia, Sharp**


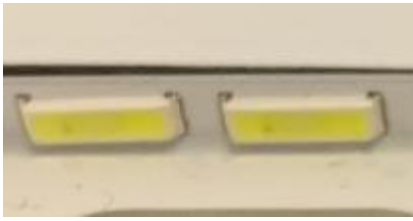

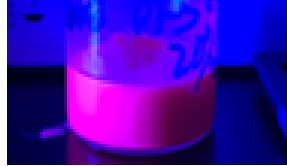

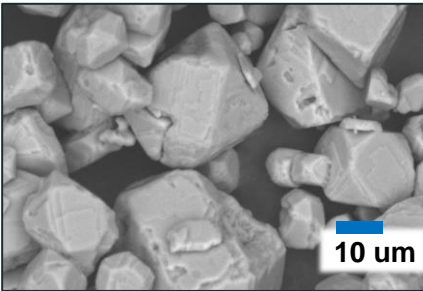
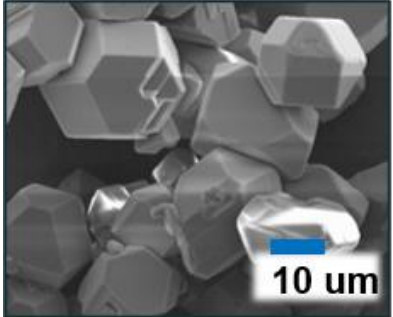
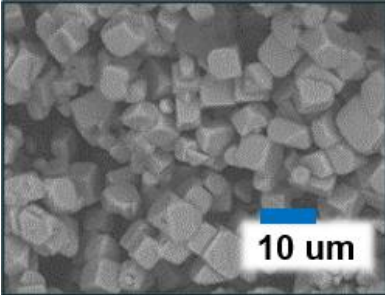
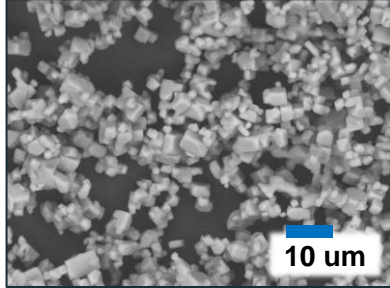
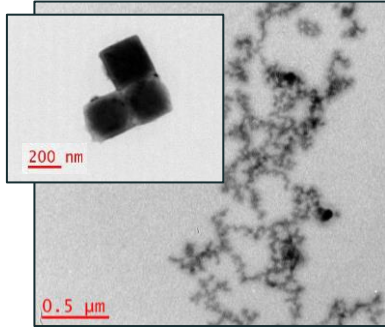


- FALD 4K HDR TVs
- DCI P3 > 96%

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

\*Partial list - GE investigation - Not exhaustive

# Evolution of **KSF** phosphor: commercialized in multiple form factors/architectures

Application	High Efficacy Lighting	WCG Display <i>edge lit</i>	WCG Display <i>direct lit</i>	WCG Display <i>micro-LED</i>	
Implementation	On LED (~3 mm)	On LED (~1 mm)	On mini-LED (~100 um) or remote film	On $\mu$ LED with longer pathlength (inks)	On $\mu$ LED with shorter pathlength (inks)
Commercial Status	Commercialized 2014	Commercialized 2014 ( <b>&gt;60 billion LEDs</b> )	Commercialized 2020	Sampling	In development
Product Example					
Avg Particle Size	25-30 um	15-20 um	3-9 um	Sub-micron	Nano-KSF
Challenges	High flux & long product life	Only moderate flux & reliability specs. 😊	Cost (easy flux & reliability)	Absorbance (thicker film architectures)	Reliability & Absorbance
Microscopy					

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

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

1

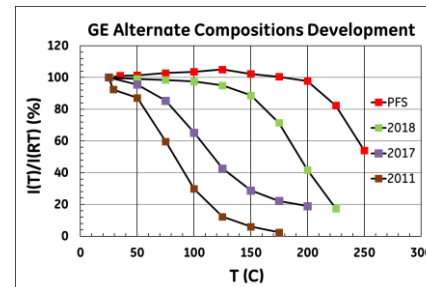
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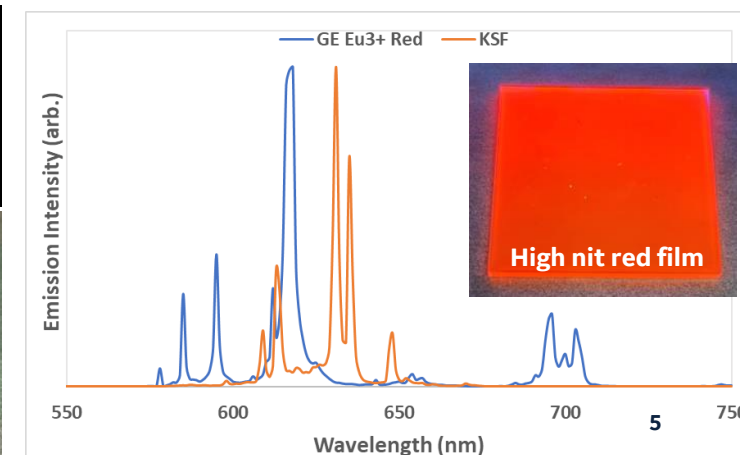
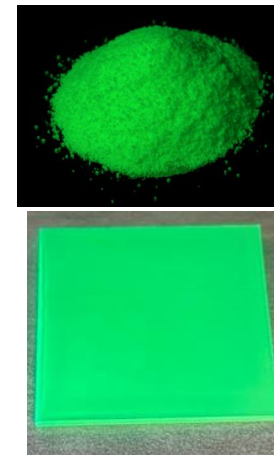
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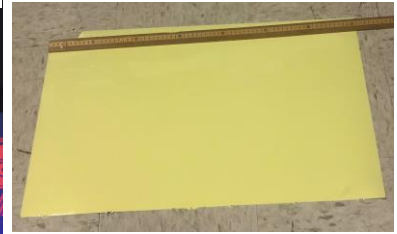
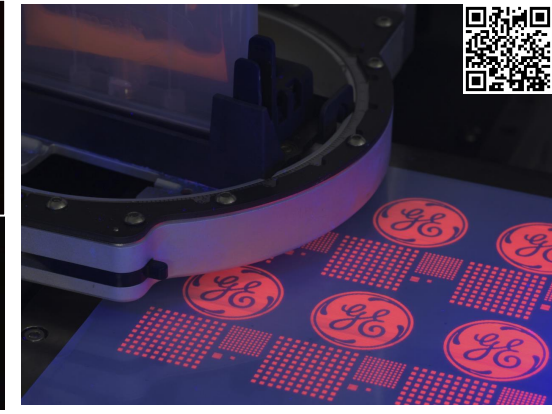
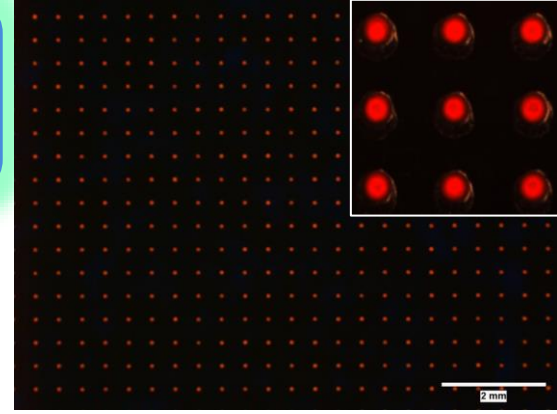
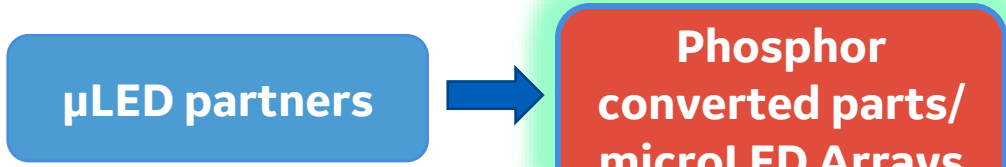
6



- Improved thermal properties & fast response
- Available in small size

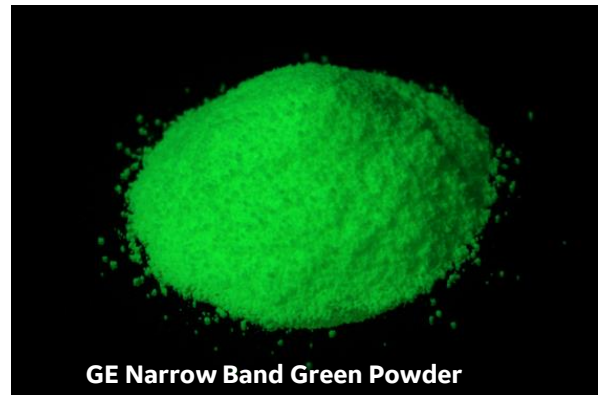
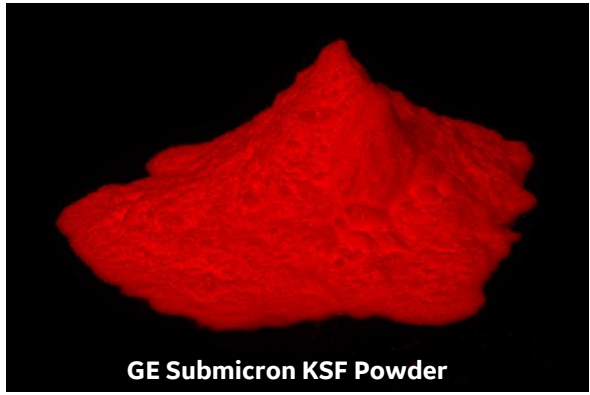
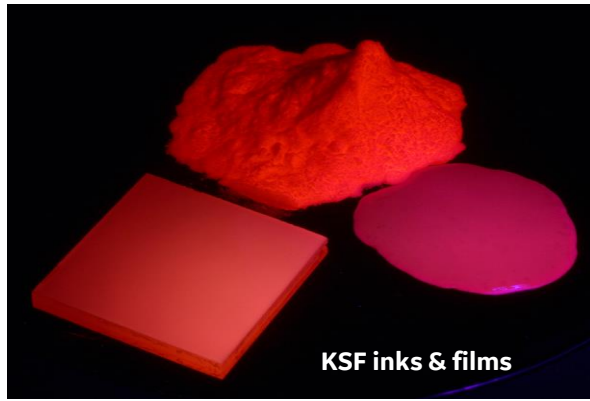


# GE Research: Vertical Integration & Collaboration to Create the $\mu$ LED Value Chain



**Collaboration:**

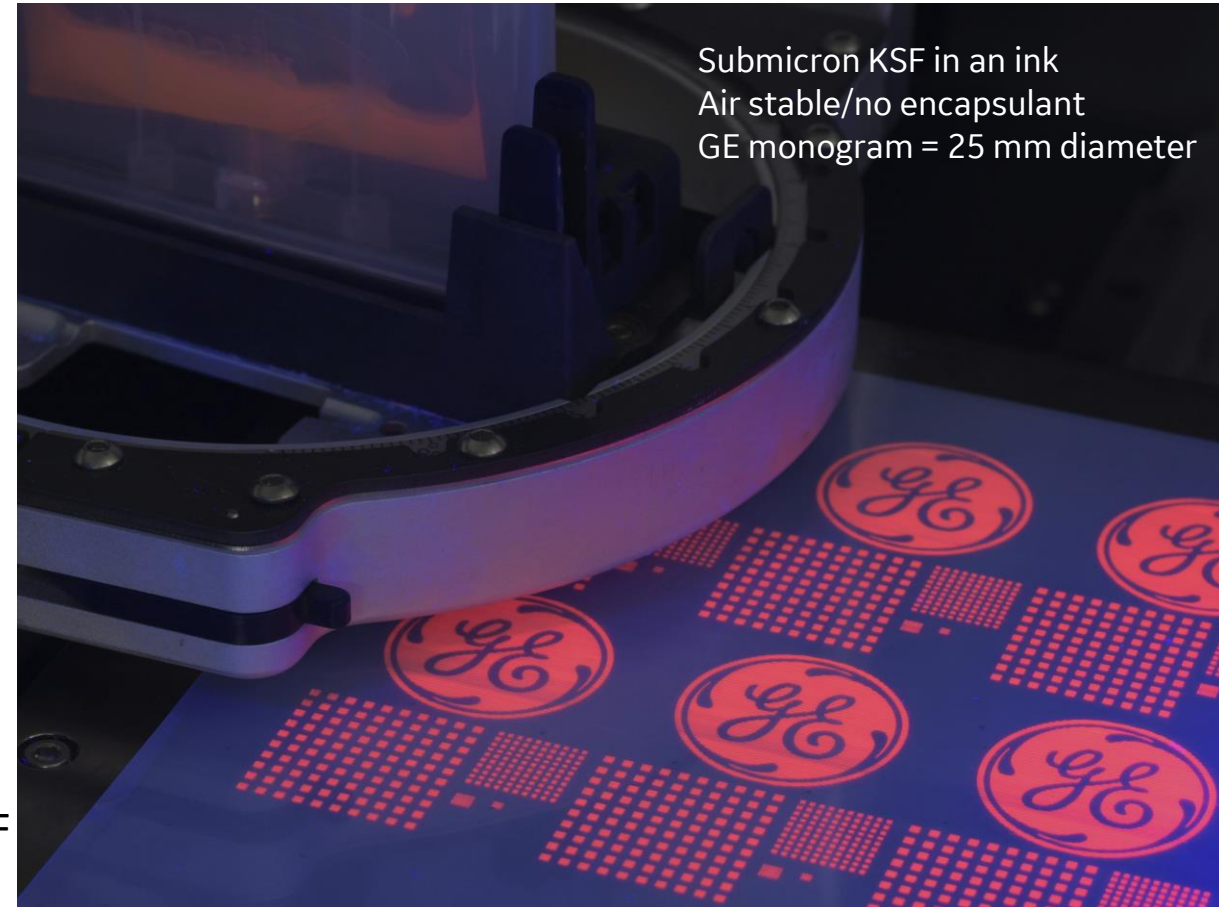
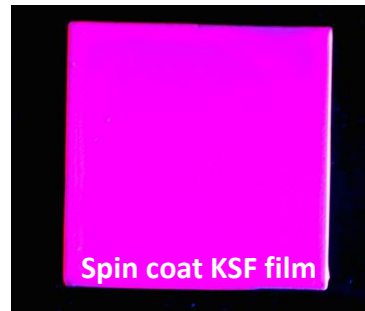
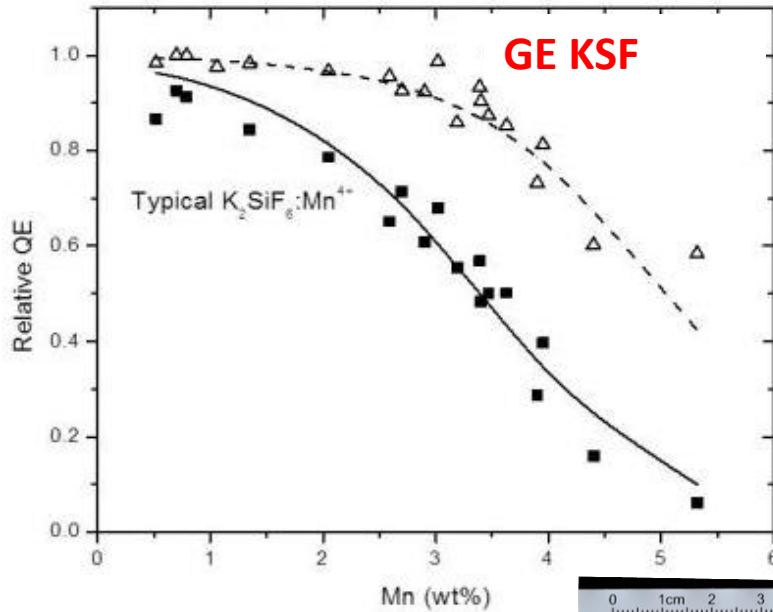
- $\mu$ LEDs
- Inks/binders
- Printing/films



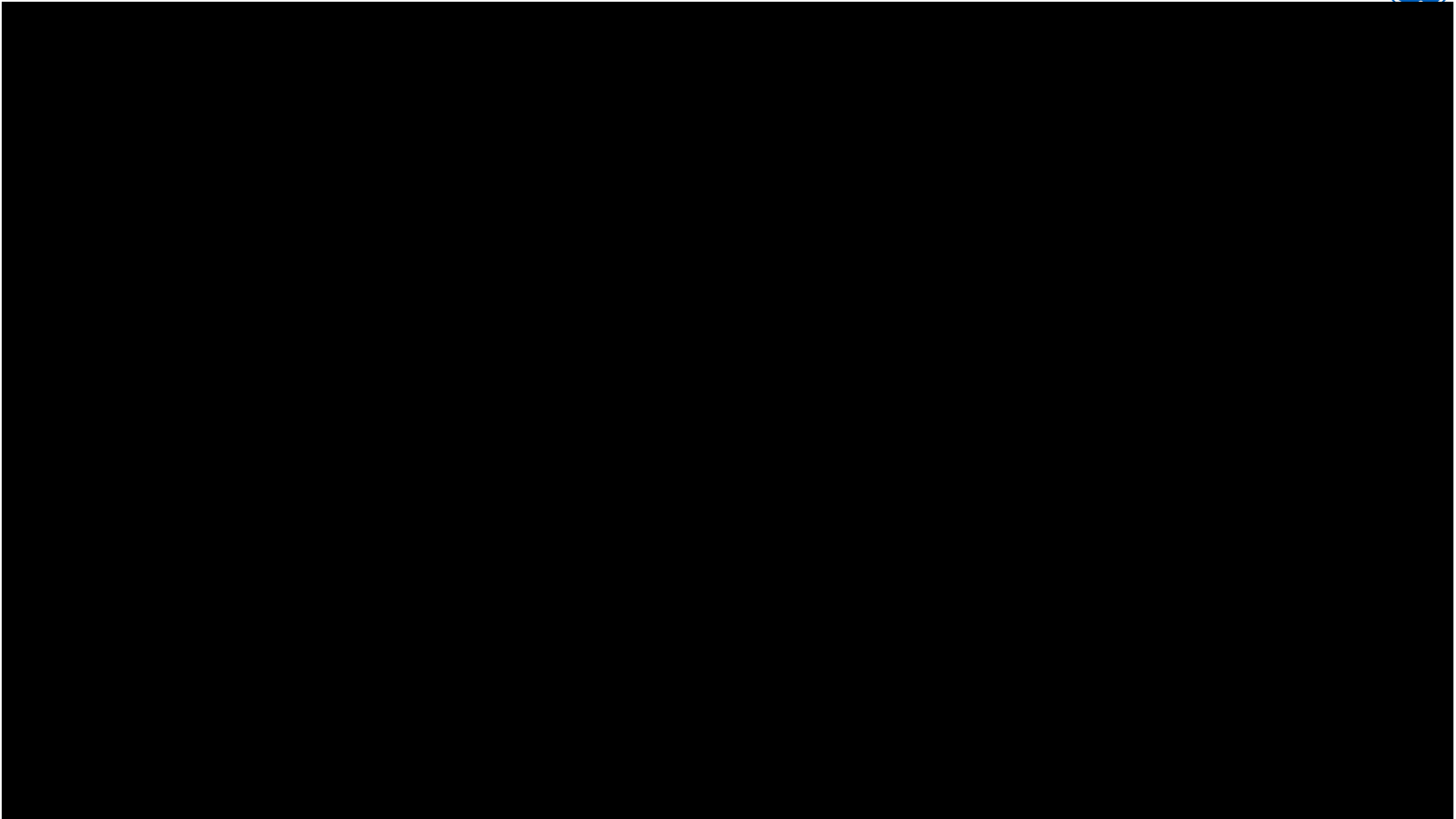
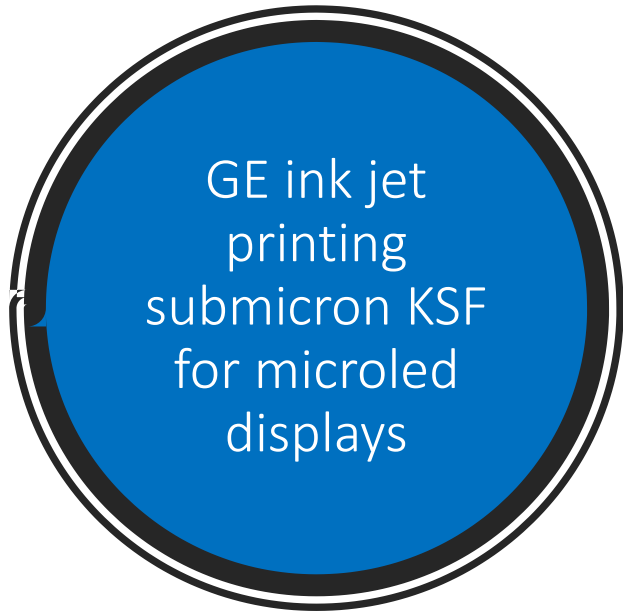
# GE KSF Inks/Ink Jet Printing for microLED color conversion



- 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](mailto:murphyj@ge.com)



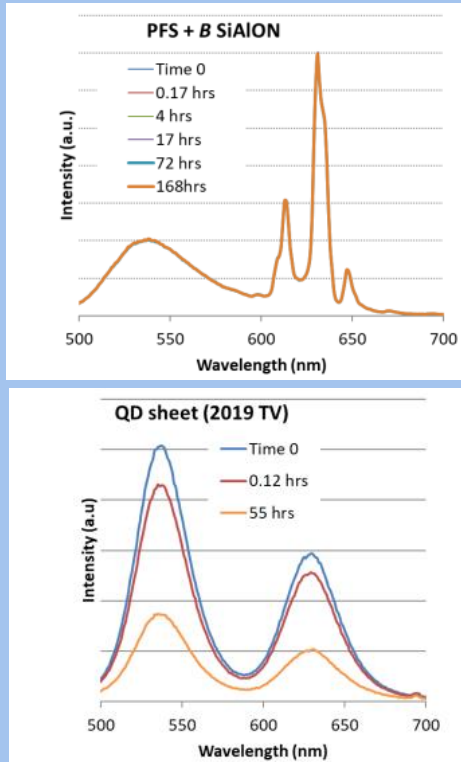
Video by Kevin Shoemaker



# KSF narrow band red phosphor: Reliable, Bright & best color gamut

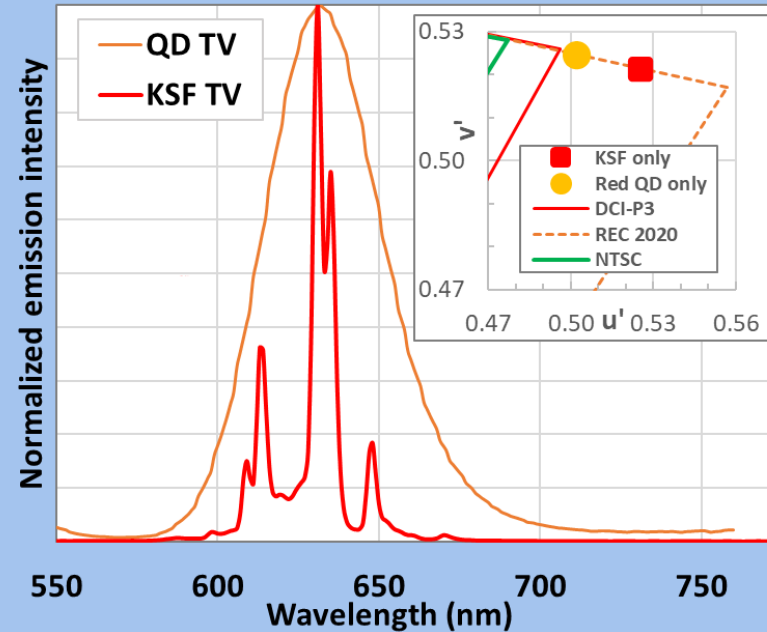


## KSF has better reliability



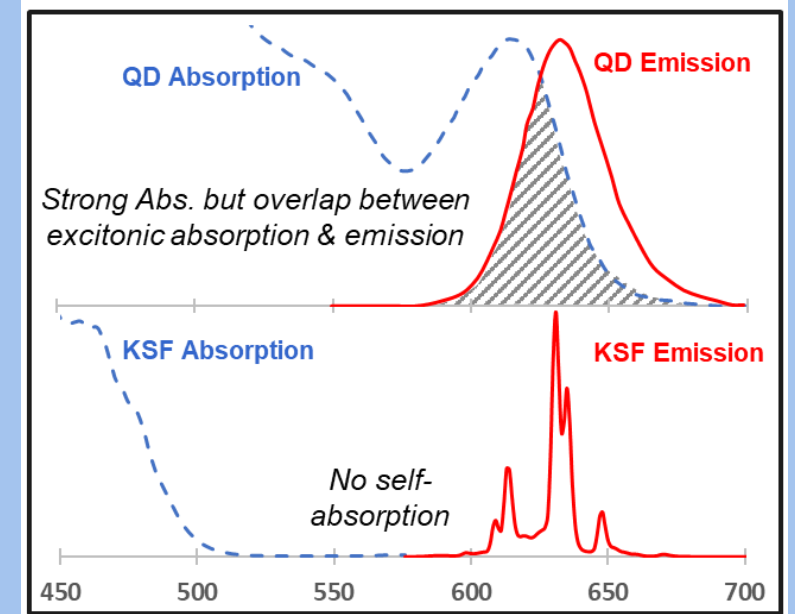
KSF phosphor can be an on chip solution because it has better reliability to air, humidity, temperature & blue flux.

## KSF has better red color



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

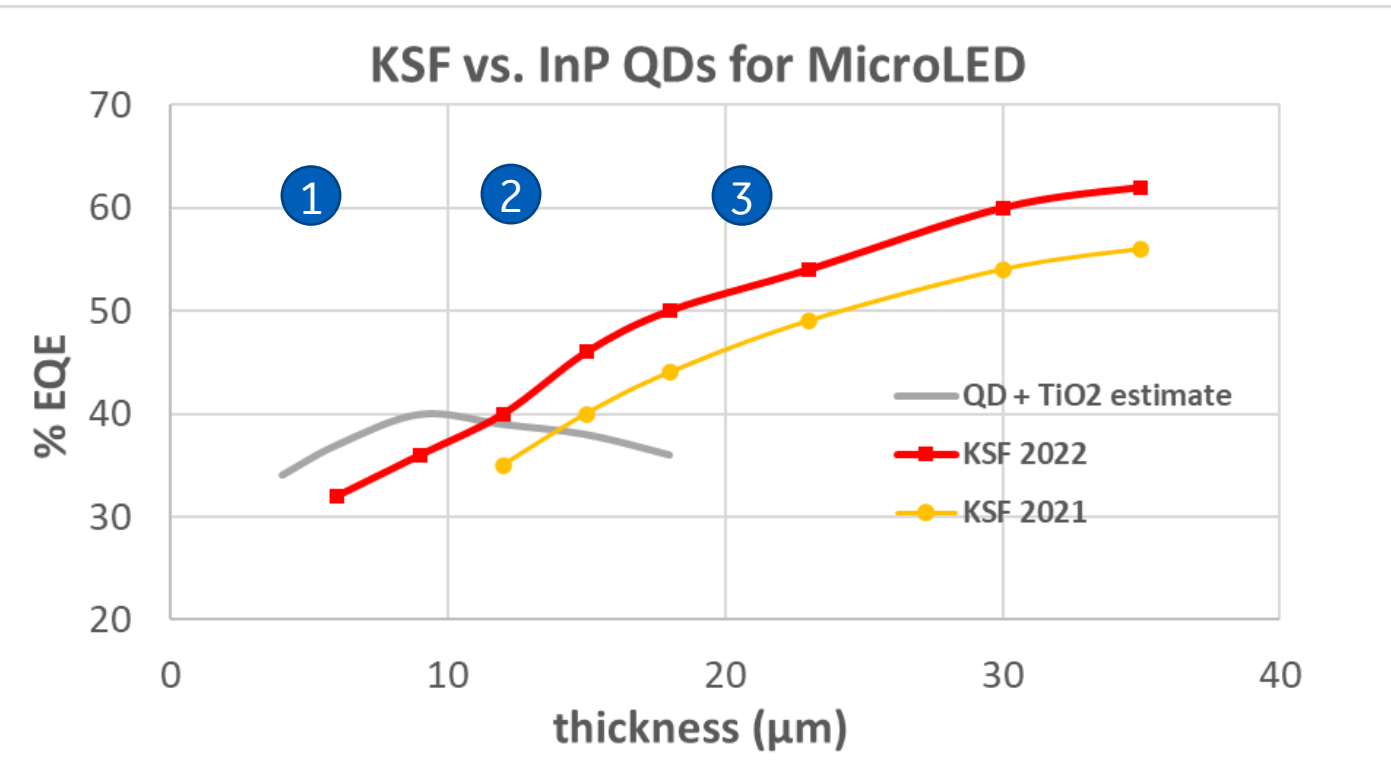
## KSF has better brightness (QE)



- 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.

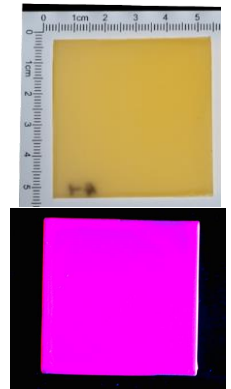
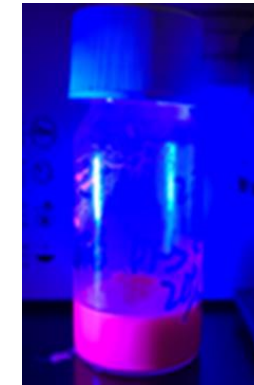
# KSF vs. InP QDs for MicroLED

**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



**GE Patented technology enables small size, high absorption KSF**

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

**Advantage  
QDs**

**Advantage  
KSF**

**Advantage KSF  
(no self absorption)**

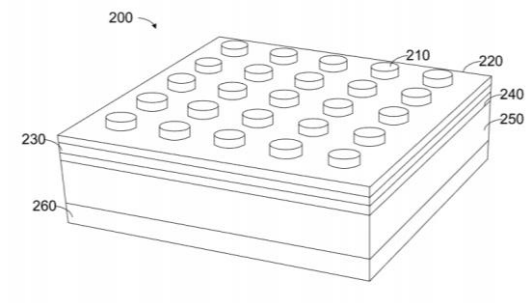


# pc-μLED architectures with reduced cross talk, higher light conversion efficiency

(pc-μLED = phosphor converted micro-LED)



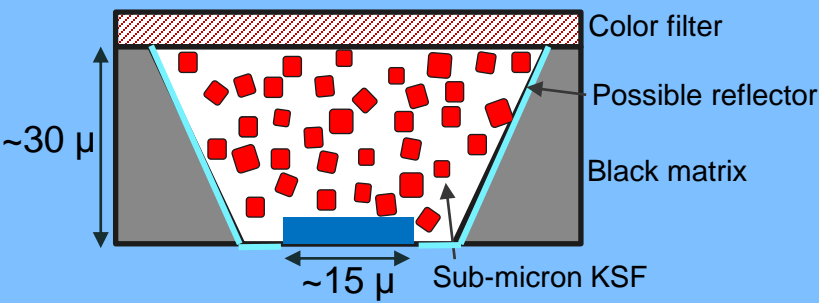
## color conversion film + dielectric metamirror



Reflects blue (light trapping), transmits red to maximize light conversion efficiency in thinner color conversion films.

Ahmed K. Design of a Transparent Dielectric Metamirror for Micro LED Displays. J Soc Inf Display. 2021. US2020/0127169A1

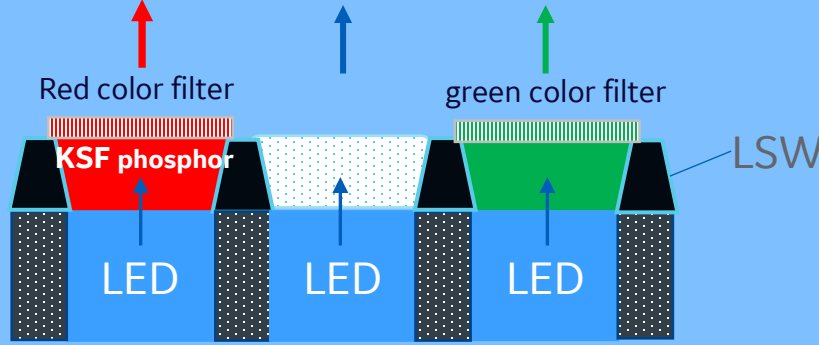
## funnel-tube array & reflective coating



- Enables thick phosphor layer with minimal color cross talk & improved efficiency
- Green phosphor may also be used to attain d65 color point

Gou F, Hsiang E-L, Tan G, Lan Y-F, Tsai C-Y, Wu S-T. High performance color-converted micro-LED displays. J Soc Inf Display. 2019

## Light Shielding Wall (LSW)



LSW improves color gamut with reduced cross talk

Onuma H et al. 1,053 ppi Full-color "silicon Display" based on Micro-LED Technology. 25-5. SID 2019 Digest

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.

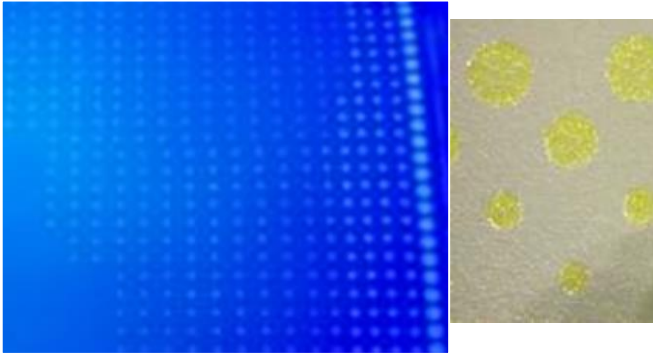
# Examples of architectures using combination of down-converters



Properties that can be enhanced by combining down-converters

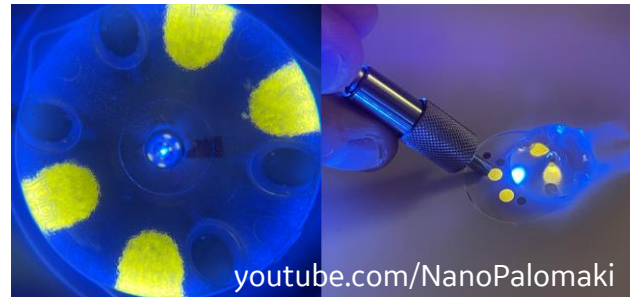
**Color** **Brightness** **Efficiency** **Uniformity** **Response time** **Cost** **Marketability**

## 1 QD Film + phosphor



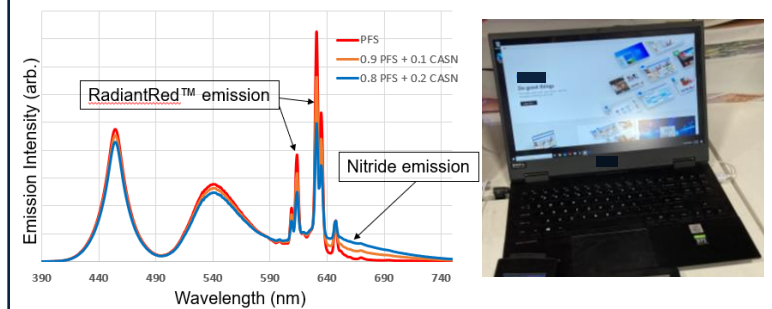
Phosphor patterned on back reflector

## 2 QD Film + phosphor



Phosphor under LED lens

## 3 KSF + Nitride + Green phosphor



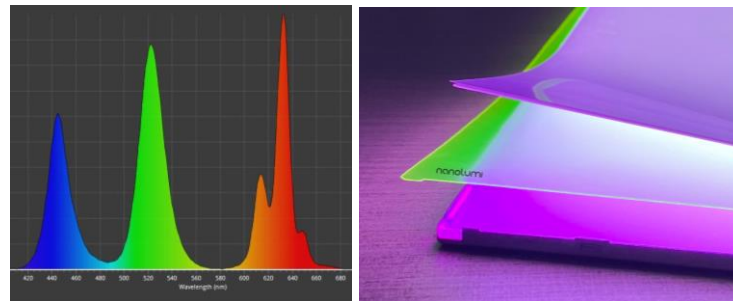
KSF + Nitride red phosphor on chip

## 4 KSF + Green phosphor



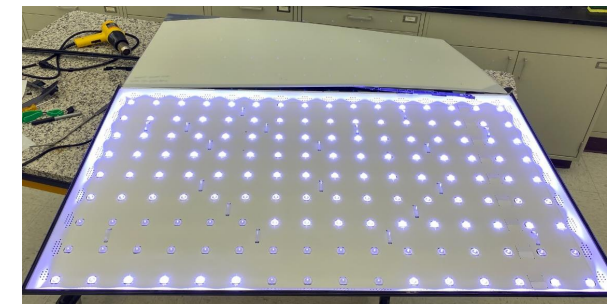
KSF in remote part (film)

## 5 KSF + green QD



KSF + Perovskite

## 6 KSF + red phosphor + QD part

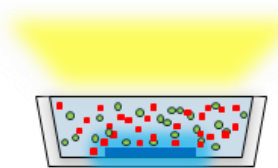


Two phosphors on chip + remote QD part

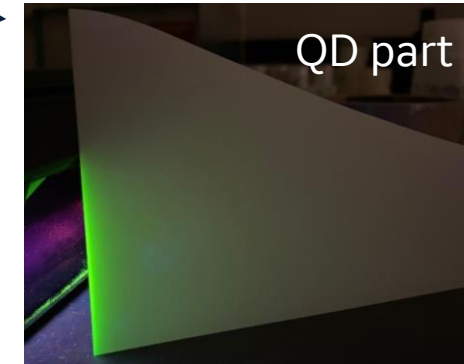
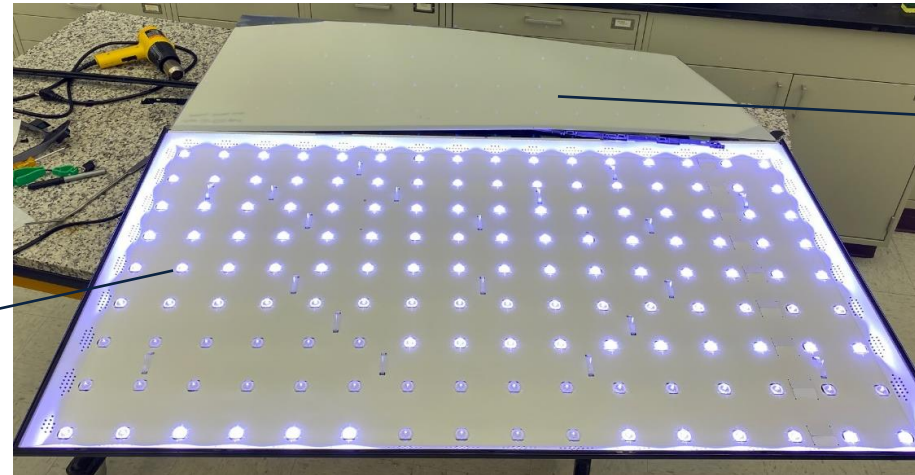
# Example 6 – Narrow-band phosphors and QDs in harmony



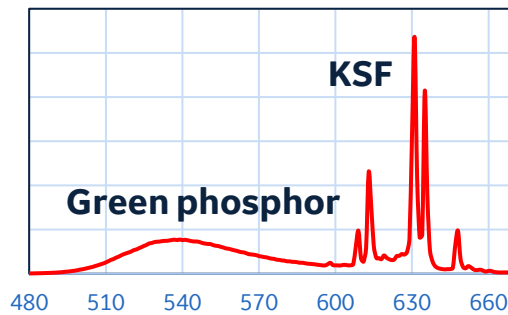
Unique combination of down-converters including:  
**KSF Red, Green Phosphor (on chip)**  
**QD red and green (remote part)**



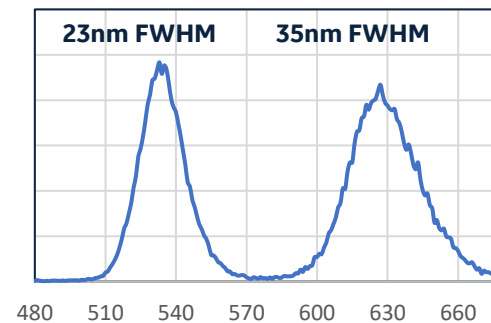
KSF + Green phosphor  
on blue LED



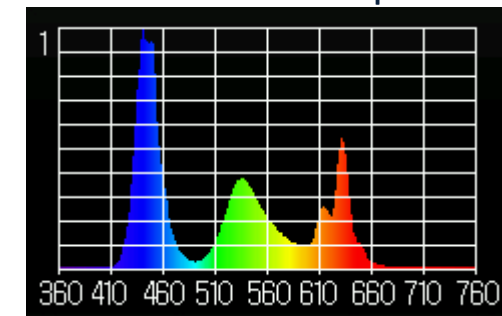
LED spectra



QD part spectra



Front of screen spectra



# Summary of Small Size GE KSF vs. QDs

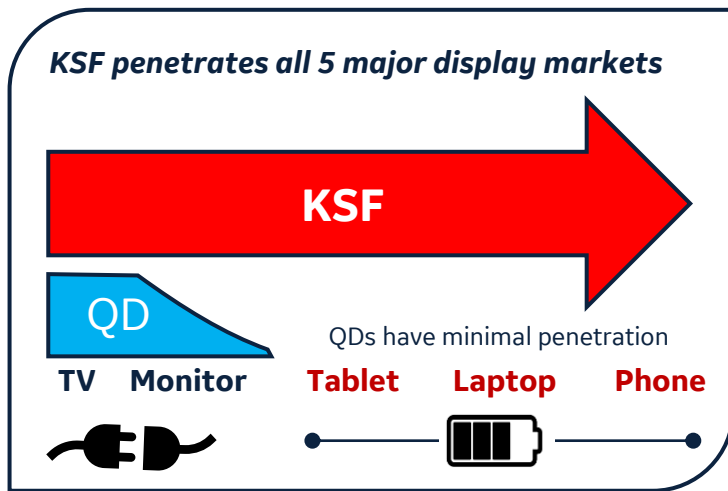


Property	KSF phosphor	Red InP QD
Color gamut	<b>5 peaks &lt;2nm each</b>	FWHM >38nm commercially
Quantum Efficiency	<b>IQE &gt; 90%, EQE &gt;60%</b>	EQE <40% [5]
Reliability to air	<b>No encapsulation necessary in commercial products</b>	Encapsulation required
Reliability to moisture	<b>No encapsulation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

- 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](mailto:murphyj@ge.com)
- For licensing inquiries contact Rachel Cassidy: [rachel.cassidy1@ge.com](mailto:rachel.cassidy1@ge.com)



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

## Exemplary Patent Assets involving PFS/KSF phosphor family

US7358542, US7453195, US7497973, US7648649, US7847309, & other issued and pending patents worldwide

## 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







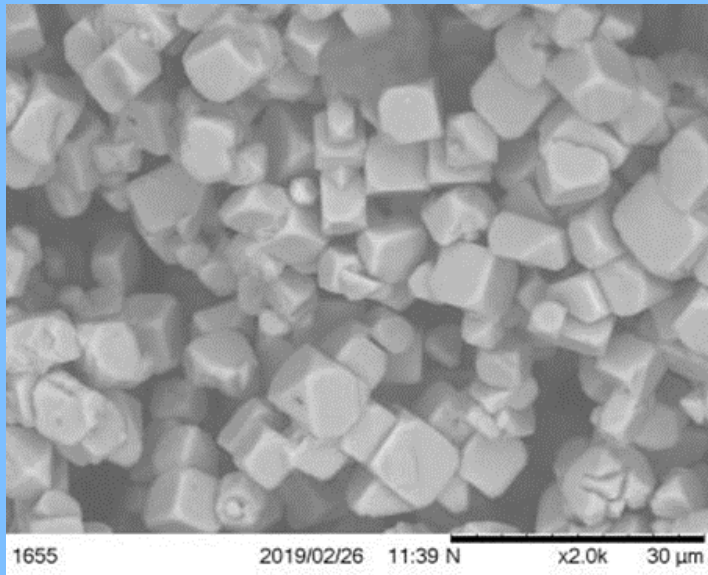
# KSF Color Conversion in Direct lit/Miniled Backlights: 3 Architectures



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

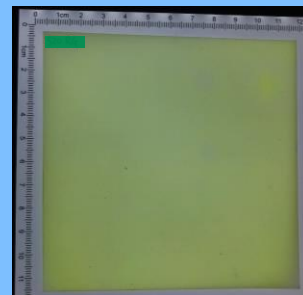
## Easiest Integration WCG Solution

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.

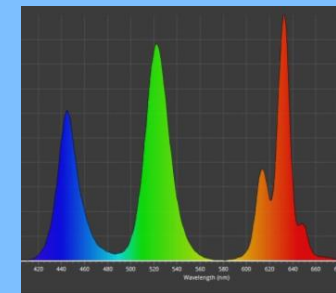
## Widest Color Gamut Solution

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<sup>1</sup>

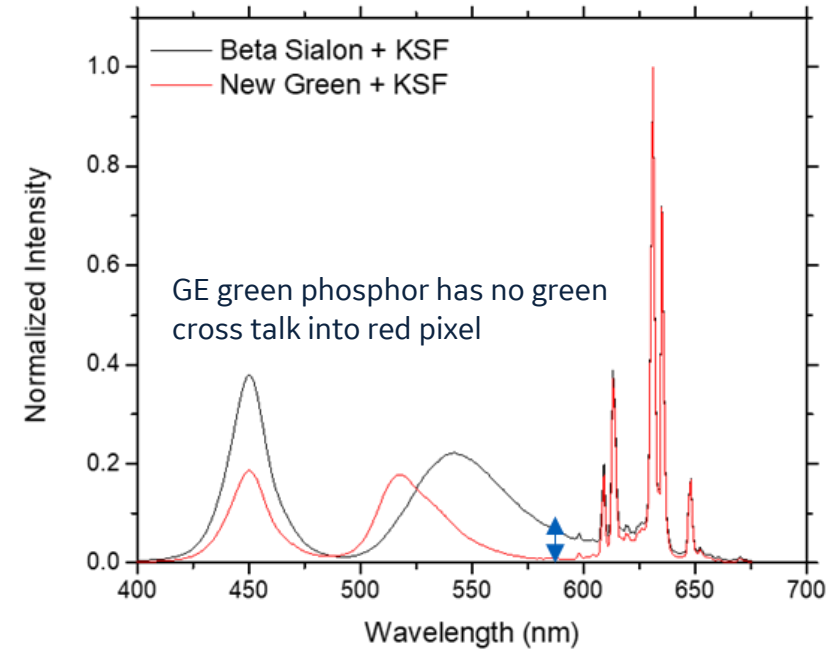
Products expected in 2021

1. Honglei Ji et al., SID Digest 2019, p. 1064  
<https://nanolumi.com/2020/news/green-perovskite-for-professional-monitors/>  
<https://www.displaydaily.com/article/display-daily/qd-materials-are-set-for-high-growth-here-s-why>

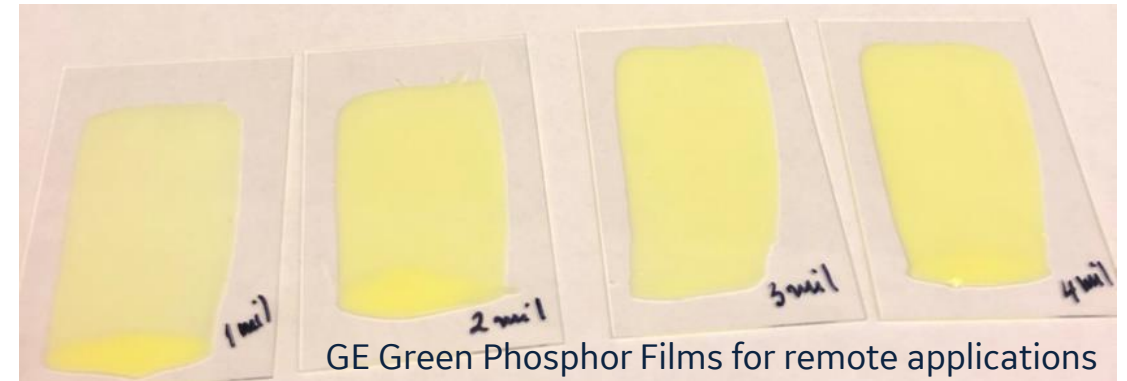
# GE Narrow Band Green Phosphors



- 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.**



material	QE	Dominant	PL decay ( $\mu$ s)
B-Sialon	100	556	2
QD	<70	540	(ns)
GE Comp 1	95	549	90
GE Comp 2	100	547	85
GE Comp 3	100	531	520

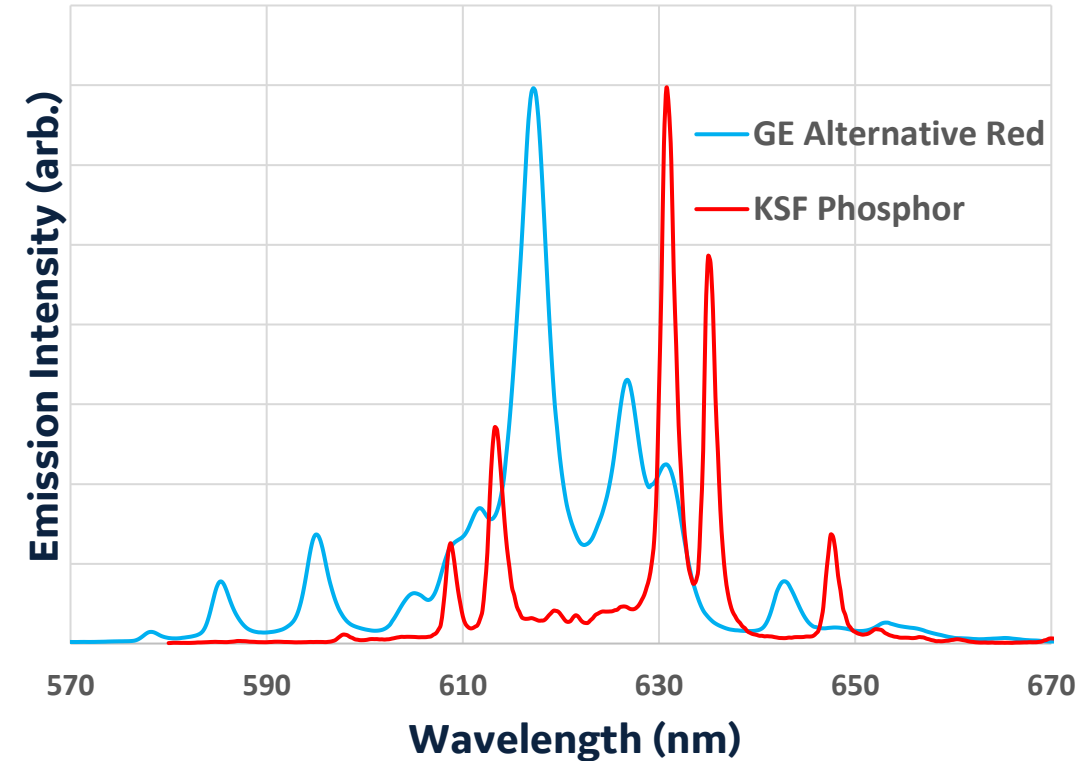


**GE's new narrow band greens can hit all requirements for next generation displays**

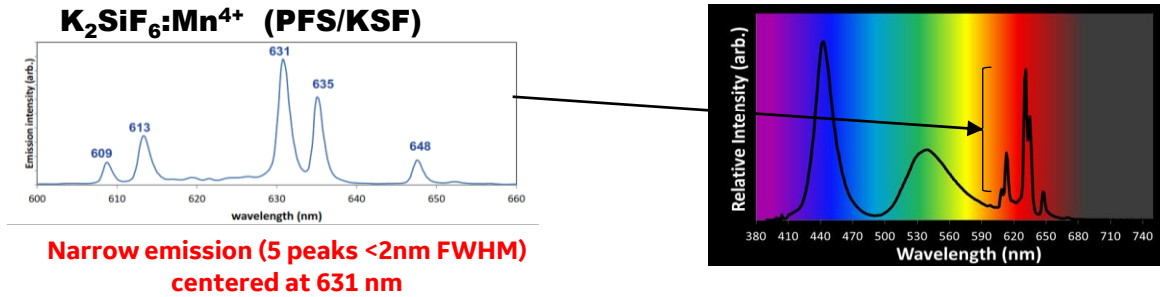
# GE Alternative Red Phosphor in Development



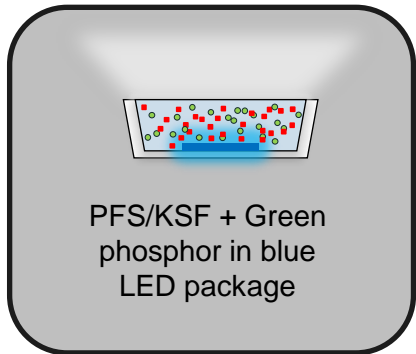
- Emission shift towards higher energy vs. KSF is ideal for lighting applications.
- Photoluminescent decay time is about four times faster than KSF for fast response time displays.
- Absorbs more strongly than KSF.
- Blending with KSF for display: Tradeoff of improved response time and less phosphor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



# Structures Requiring A Display License to GE PFS/KSF Patents

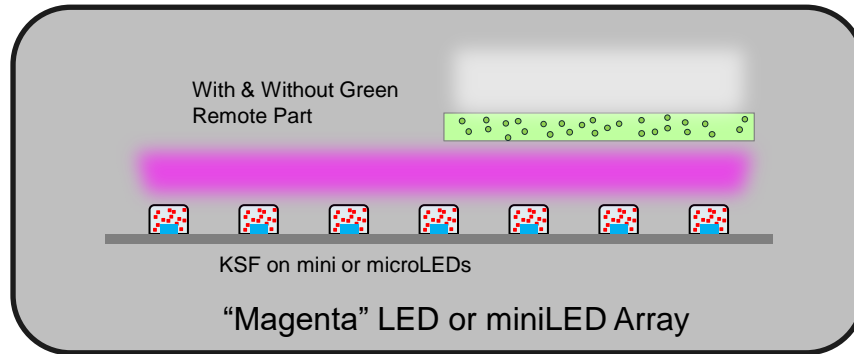
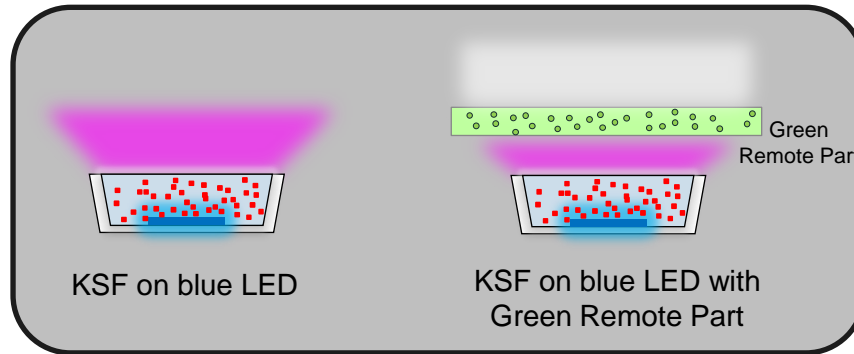


## On-chip Configuration



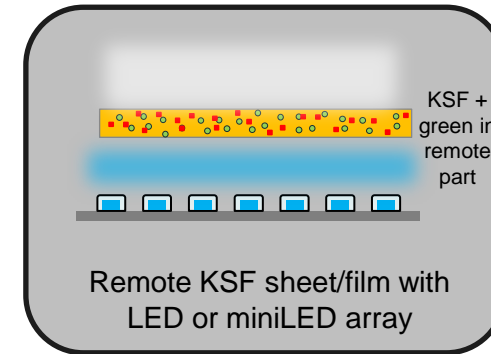
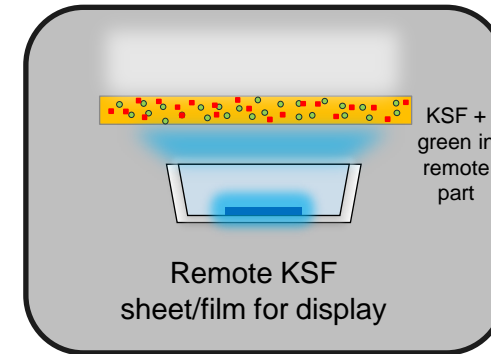
Narrow-band White Light LED Package for Display

## Magenta LED Configuration



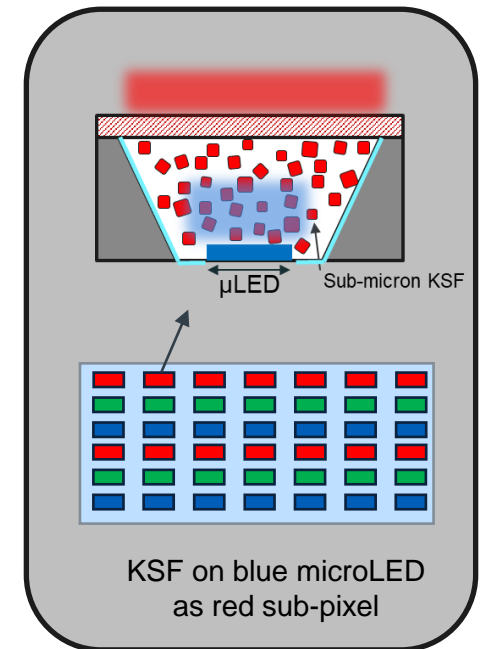
Magenta LED Package for Display – PFS/KSF remains in LED package

## Remote Part Configuration



PFS/KSF in the Remote Sheet/Film with LED or miniLED array

## microLED Configuration



PFS/KSF converts blue microLED to red sub-pixel