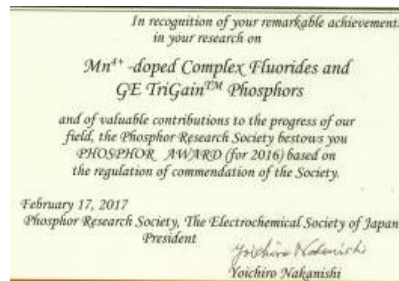
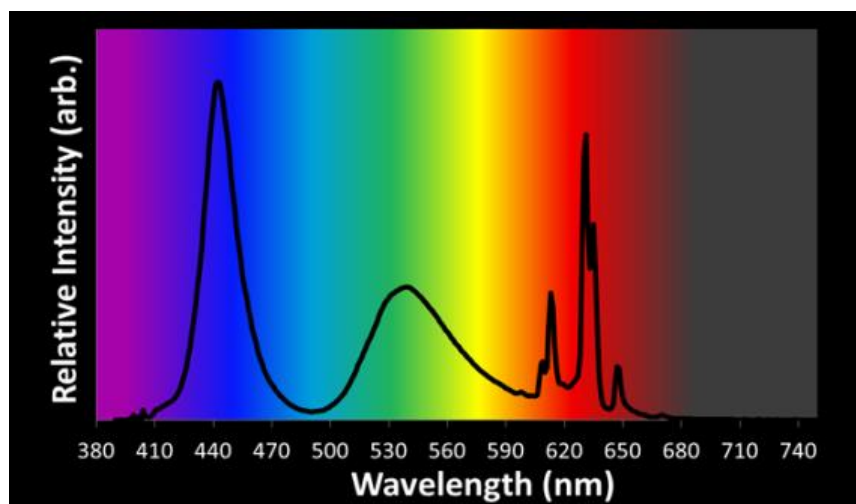


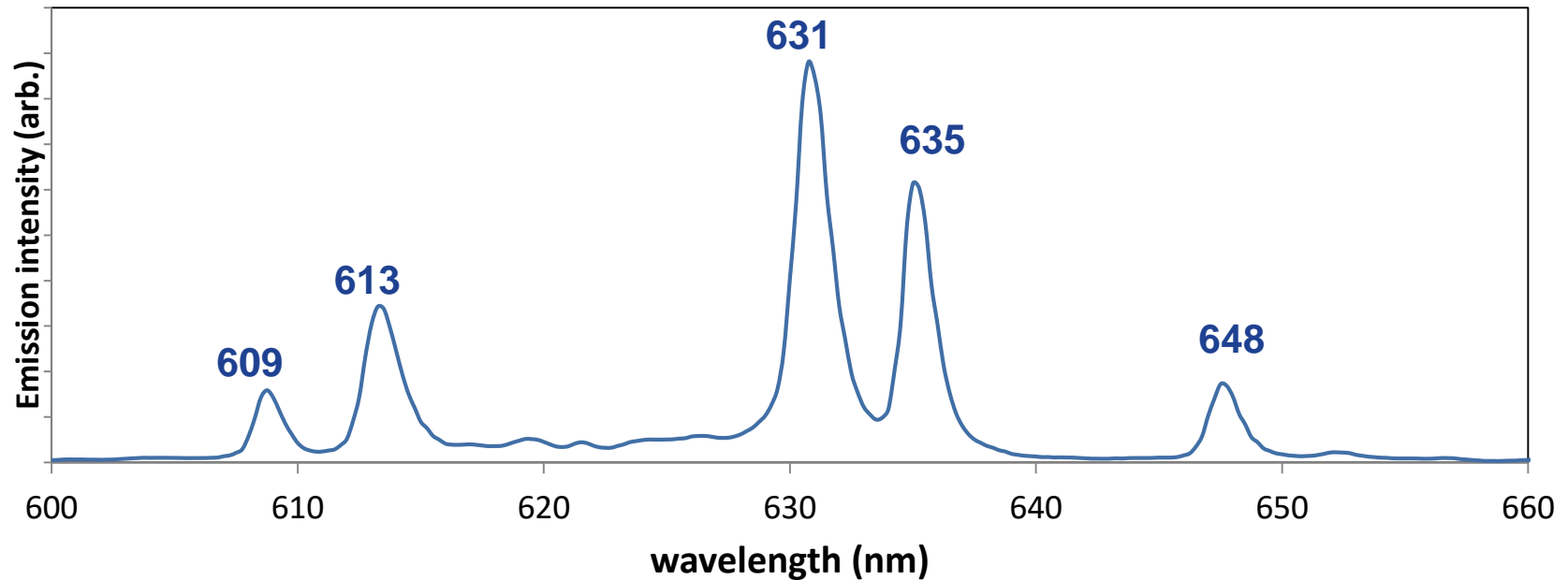
GE $K_2SiF_6:Mn^{4+}$ (PFS/KSF) Phosphor: Market Leading Wide Color Gamut Technology & Path Towards Enabling Next Generation Displays

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Introduction: Properties of $\text{K}_2\text{SiF}_6:\text{Mn}^{4+}$ (PFS/KSF)

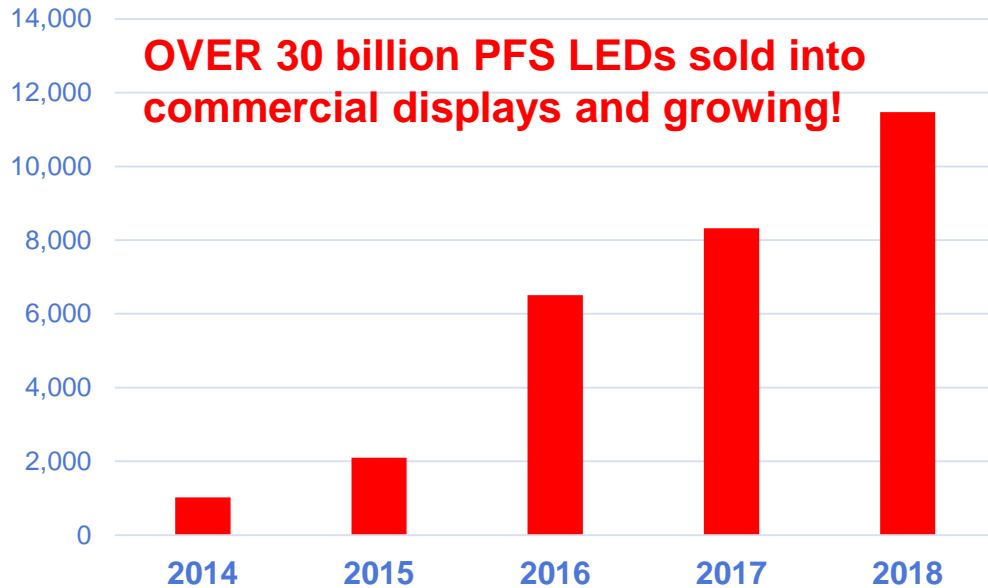


- Narrow band red emission centered at 631nm (5 peaks <2nm FWHM) matches rec.2020 requirements well enabling wide color gamut displays.
- On chip solution, RoHS compliant, no design modifications necessary
- Stable in air & does NOT require encapsulation
- **Patent License required from GE for use with blue LED**

Cost Effective, Commercialized, Wide Color Gamut Solution

PFS/KSF LED| Display Market Adoption & GE Global Business Strategy

LEDs CONTAINING PFS – ACTUAL DATA!



Figures in millions

- 20 LED companies licensed to GE's PFS/KSF patents for display purposes (majority of LED production)
- Several more discussions under way
- GE and Current Lighting Solutions partner for the licensing, manufacturing, sales, and advancement of PFS/KSF TriGain(TM) Technology.
- Continual improvements give superior on-chip performance to expand into next gen display platforms (i.e. Mini/Micro LED's, Films)
- PFS/KSF is found in all display platforms where LED backlights are required

In just 3 years PFS has gained rapid acceptance in displays where it is now the leading red material for wide color gamut LCD BLUs – Yole Report 2017



Where PFS can be found TODAY*

Achieved market dominance across top 4 display sectors

Smart phones

Samsung, Apple, Huawei, LG, BLU, Razer, Red



More XR models have been sold than XS

Laptops & Monitors (gaming)

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



Gaming laptops
144 Hz Refresh rate

Tablets

Apple, Samsung, Lenovo, Huawei, Microsoft, Asus



Televisions

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

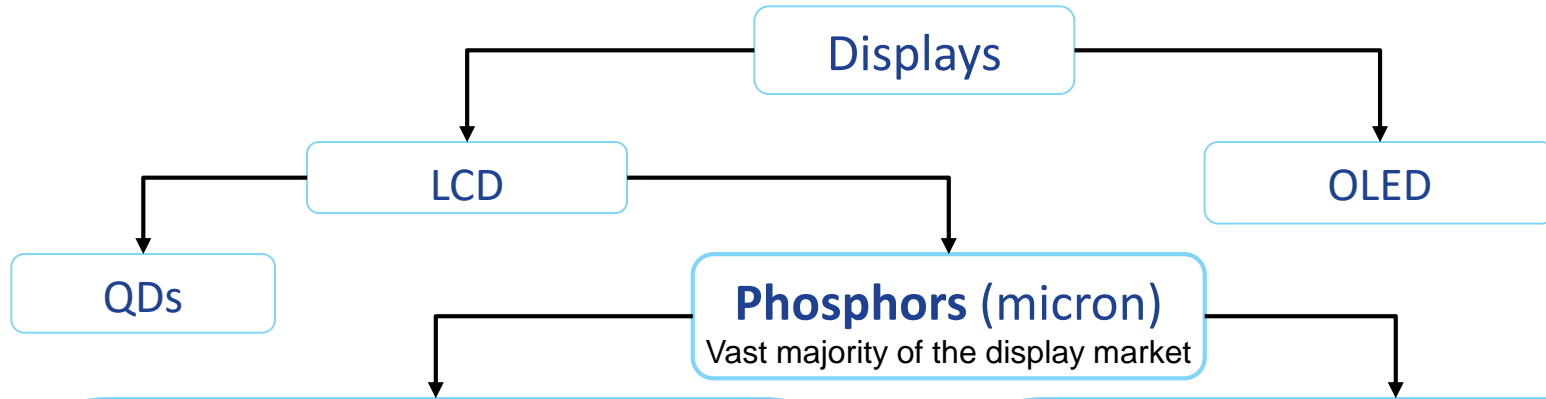


- FALD 4K HDR TVs
- DCI P3 > 96%
- Top Selling Samsung TV

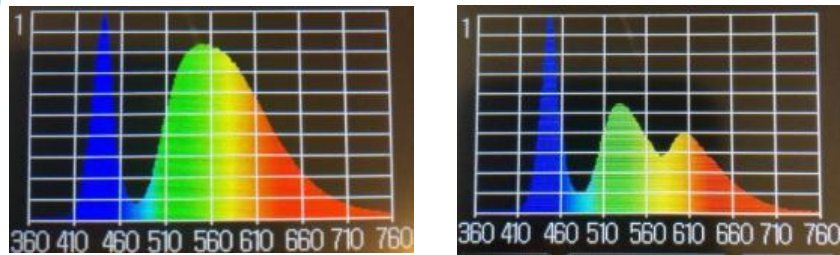
<https://pocketnow.com/apple-sold-more-iphone-xr-models-than-iphone-xs-and-xs-max-combined>

*Partial list based on visiting four (4) stores – GE investigation – Not exhaustive

Color in Displays Today

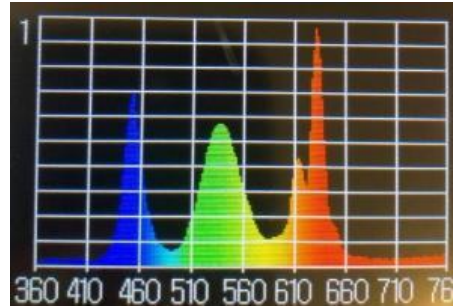


Broad Band Phosphors



- ✓ low cost
- ✓ On chip reliability
- brightness vs. color gamut trade off

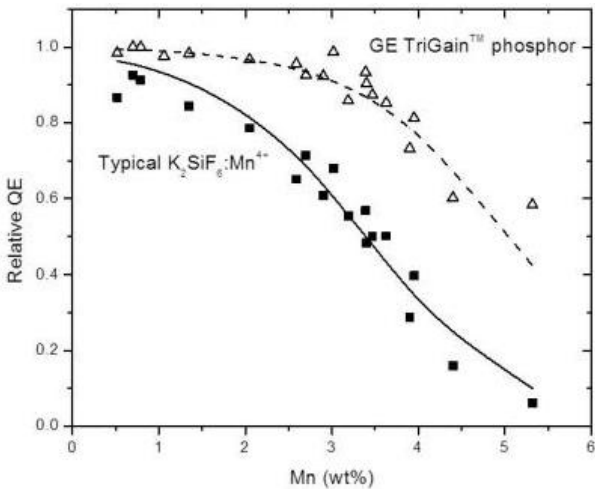
Narrow Band Phosphors



- ✓ Wide Color Gamut
- ✓ High Brightness
- ✓ On chip reliability
- ✓ low cost
- ✓ Fast penetration into display market since 2015

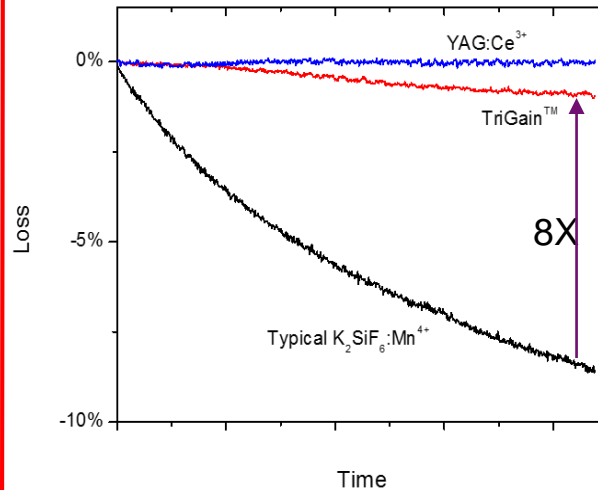
PFS/KSF Phosphors by GE

Few defects enable stronger absorption & wide range of particle sizes



Less concentration quenching enables higher $[Mn^{4+}]$

High Reliability under high blue flux

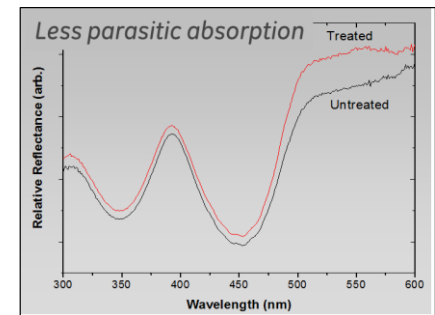


8X Reduced damage under high blue flux enabling on chip medium powered packages

Excellent Reliability under High temp./humidity

HTHH Testing: 85°C/85%RH at 150 hrs.

Sample	Initial QE/Abs	$\Delta(QE \cdot ABS)$
Typical PFS	95/72	-14%
TriGain™	100/70	-2%



Higher QE & less HTHH degradation

Red phosphor that enables best on chip performance & reliability

Comparison of Commercialized QDs to Narrow Band Phosphors for LCD BLU TV

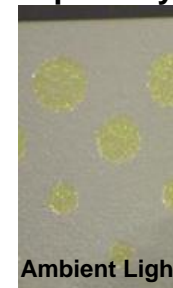
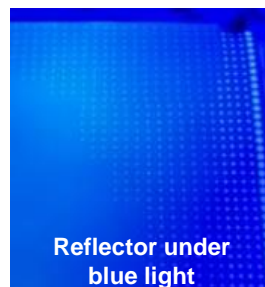
(March 2019: GE purchased 2 TVs from retail store)

TV/part Characteristic	PFS + green phosphor	QD Containing
Phosphor configuration	<ul style="list-style-type: none"> On chip, unencapsulated Phosphor area <0.8% QD area 	<ul style="list-style-type: none"> Remote, Encapsulated QD covers full screen area
49" TV Cost (Same brand)	\$699	\$899
Estimated Yearly Energy Cost (49"/65")	\$14/\$17	\$15/\$20
Best Selling TV Rankings https://lcdtvbuyingguide.com/top10.shtml	1	9
Rel. Quantum Efficiency, %	>90%	<70%
Thermal Quenching at 100 °C (next slide)	<3%	>20%
Color Shift (next slide) (25W/cm ² blue flux, 55 hrs.)	$\Delta X \ \& \ \Delta Y < 0.001$	>30 times color shift of PFS + green
Motion Rate (65") Manufacturer's data	240 Hz	240 Hz
80%/100% Response Time* *Rtings.com measurement	4.7ms/12.8ms	5.1ms/12.9ms
Color Gamut (DCI P3 uv) * (next slide) *Rtings.com measurement	92.13% (PFS more narrow than red QD)	94.86% (Green QD more narrow than green phosphor)
Supply Chain	20 licensees provide LED packages	???



First Commercialized QD/phosphor Hybrid TV?

- LCD system primarily determines response time
- Filters play a significant role in color gamut
- PFS commercialized in both full array and edge local dimming backlights

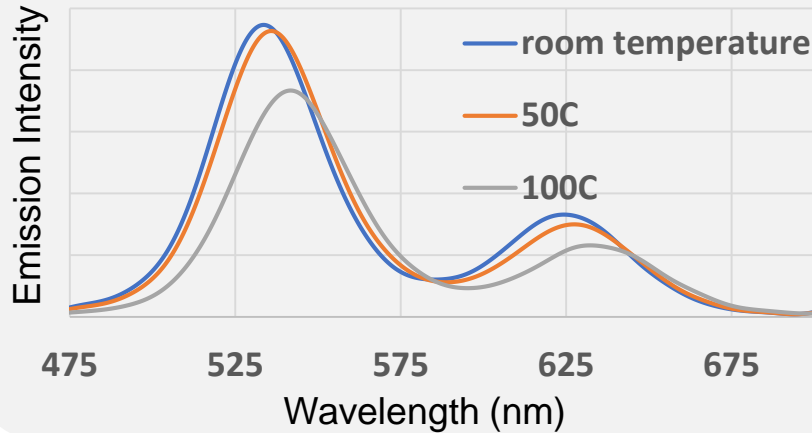


- Back Reflector of tested QD TV contains garnet phosphor.
- PFS Containing TV does not.

Accelerated Life Tests:

QD TV Part Reliability Testing vs. Phosphors

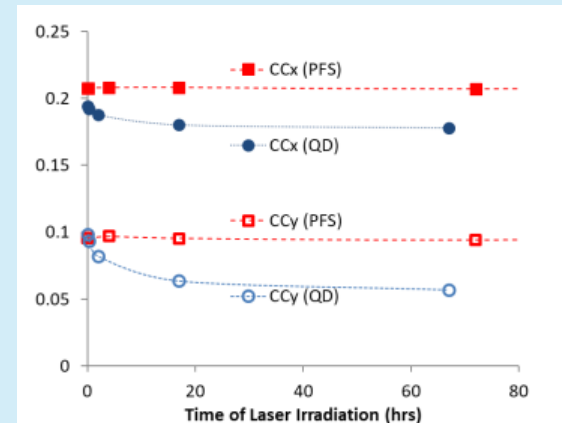
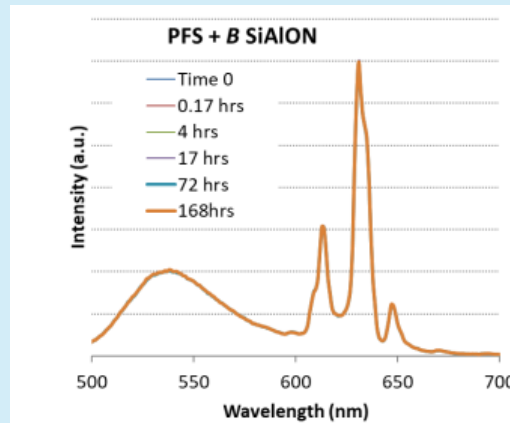
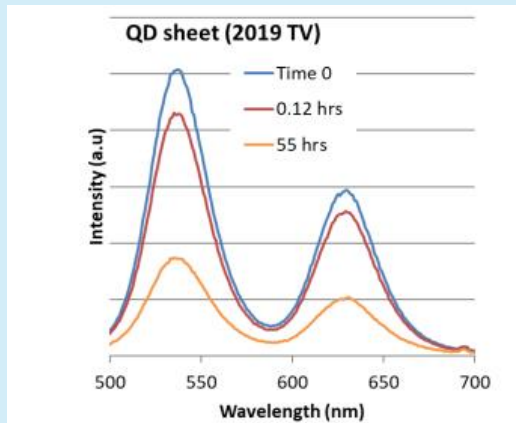
Thermal Quenching of QD TV Part



	FWHM (nm)	peak (nm)	FWHM (nm)	peak (nm)	relative intensity, %
phosphor TV	50	536	< 30	631	NA
QD TV	38	537	41	630	NA
QD part RT	40	534	48	625	100
QD part 50C	41	537	49	629	96
QD part 100C	44	543	51	635	78

- PFS shows minimal thermal quenching at 100°C
- QD part has significant filtering in TV

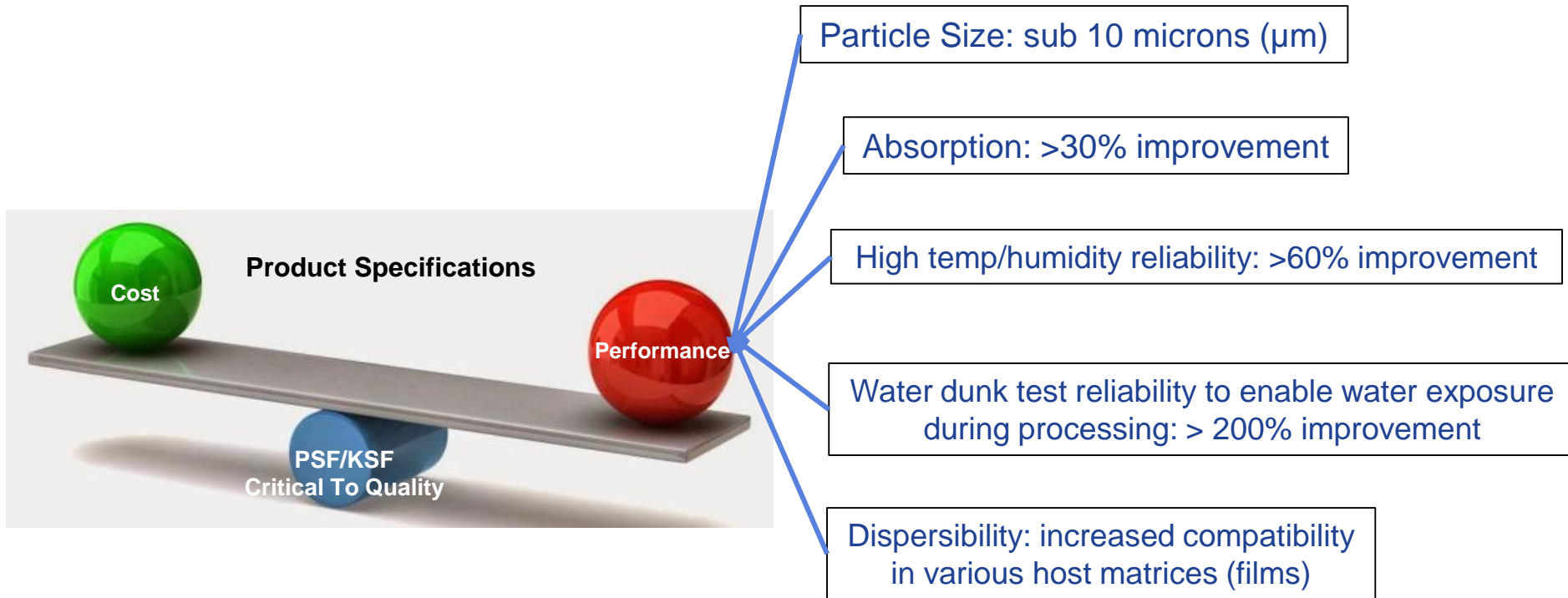
Blue Flux Degradation (25W/cm²) of QD TV Part



- PFS shows no drop in brightness or color shift
- QD part shows significant flux degradation and color shift

Next Generation PFS/KSF:

Multiple Types are at Pilot Scale



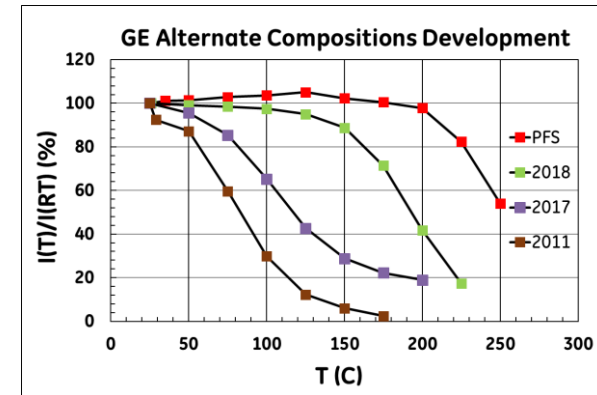
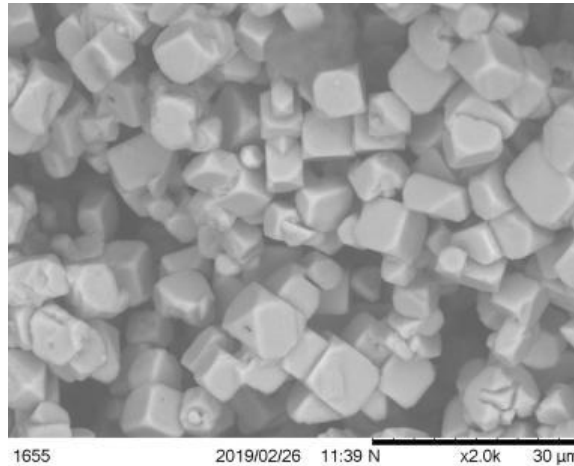
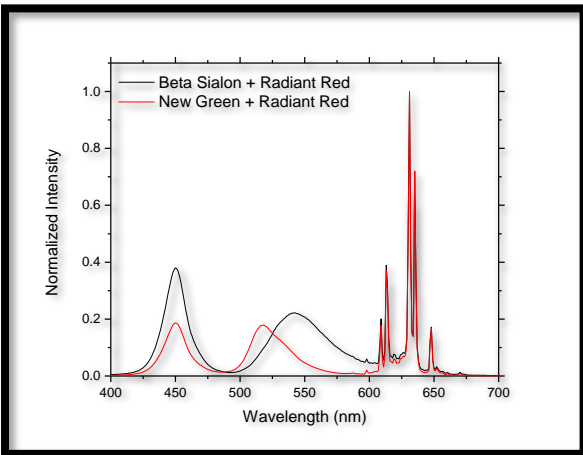
- Depending on Licensees' needs, additional patented processes have been developed by GE
- Balancing performance and cost for LED packages and remote parts (films).

GE Phosphor Roadmap to Enable Next Generation Displays

Narrow Band Green Phosphor

Small Size PFS Phosphor

Faster Red Phosphor



- **New GE NBG Phosphor:**
 - enables > 25% gamut increase vs. β -Sialon.
 - FWHM < 35nm to minimize emission into red pixel.
 - optimization in progress.
- Other companies also developing NBG phosphors
- Collaborations ongoing for hybrid green QD + PFS.

- Diversity in LED size requires diversity in PFS size.
- 3 μ m size with IQE > 90%.
- Enables CSPs, miniLEDs and thin (remote) films.
- Customer sampling underway for licensees.
- Submicron PFS Development is in progress.

- **30% faster PL decay time vs. PFS with same QE.**
- Continued optimization: Improved thermal quenching.
- Enables response times similar to QD gaming monitors.
- Customer sampling underway

Color Conversion in Next Generation Displays: The next 5 Years

- LCDs will continue to dominate the market
- MiniLEDs will reach >15% of TV, monitors, and automotive displays
- MicroLEDs will be a niche commercial product with only smart watches > 15% market penetration

Potential Market Disruptions:

- Narrow Band Green Phosphors
- Submicron phosphors with good reliability
- Hybrid: QDs + phosphor
- QD on chip (need thermal & flux stability)
- QD unencapsulated (O_2/H_2O stable)

← Advantage Phosphors

→ Advantage QDs

Standard
LCDs

on chip
pc-miniLEDs

Remote part
pc-miniLEDs

Unencapsulated
microLEDs

Encapsulated
microLEDs

← Higher market share

← More certainty/more available supply chain

Higher Risk/Complexity →

Higher Cost →

- Phosphors, QDs, and OLED will continue to coexist in next generation displays
- Phosphors will remain the most used technology
- Narrow band phosphors provide the wide color gamut to compete with QDs, OLED

The 5 Big Myths of Phosphors for WCG Displays

Here are the facts.....

Myth 1. OLED and QDs are the only 2 color (conversion) solutions for wide color gamut (WCG) displays.

Fact 1. Phosphors are used in more displays than OLED and QD displays combined and are the industry standard used for displays having wide color gamut (DCI P3 >90%)

Myth 2. Phosphors are broad band emitting luminescent materials.

Fact 2. There are many examples of commercialized phosphors that have more narrow emission than InP QDs.

Myth 3: Red QDs produce a color gamut that is higher than PFS phosphor.

Fact 3. PFS emission is more narrow than a red InP QD, enabling higher gamut when using the same green.

Myth 4: PFS containing displays have response times that are too slow for fast action (gaming/sports) and local dimming.

Fact 4. Several PFS-containing gaming laptops with sub 3ms response times and FALD TVs were found in our local big box store.

Myth 5: QDs have similar quantum efficiency (QE) & reliability (oxygen/humidity/temperature/blue flux) to B-SiAlON/PFS phosphors.

Fact 5. PFS is commercialized in over 30 billion on chip packages since 2015. QDs are used in remote part configurations that add cost because of reliability issues. In commercialized parts, QDs have QE<70% & FWHM >40nm.

Narrow Band Phosphors should be included in discussions around color for next generation displays

Summary

Phosphors will continue to be the dominant color conversion technology in next generation displays!

1. LCDs will continue to be the dominant cost effective display type.
2. PFS/KSF is penetrating into LCD market at a rate >5X that of QDs.
3. Reliability, supply chain (20 licensee established) & cost advantage are significantly in favor of phosphor (PFS/KSF) on chip color conversion for wide color gamut LCD displays.
4. PFS/KSF phosphors recently commercialized in fast action/gaming laptops and phones, FALD TVs & a 3D holographic media machine. Phosphor decay time is NOT limiting the LCD response time.
5. There continues to be investment by multiple companies for narrow band phosphor development for next generation displays. Phosphors are improving/evolving just as other technologies evolve.

Exemplary GE Patent Assets involving PFS/KSF phosphor family

US7358542, US7453195, US7497973, US7648649, US7847309, US8057706, US8252613, US8906724, US9376615, US2016/0024378, US2015/0315461, US2015/0315462, US2015/0364655, US2015/0361335, US2015/0361336, US2014/0264418, & other pending patents worldwide

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