# Response to RoHS Exemption Request 2013-5 Open Comment Period

December 2013

# Agenda

- Nanosys introduction
- Market Survey of Color Gamut and Efficiency
- Cd-based quantum dots provide the most energy efficient solution to high color gamut LCDs
- Status and future of non-Cd quantum dots
- Impact on environment

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# About Nanosys

- First company to focus on Quantum Dots for Electronics
- #1 Quantum Dot IP Position
  - 211 world-wide granted patents, 73 pending
  - Technology from MIT, LBL, Life Technologies, Philips-Lumileds
- Developer of both CdSe and InP Quantum Dots
  - First InP dots sold in 2006 to research and education markets


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# Bringing CdSe Quantum Dots to Market

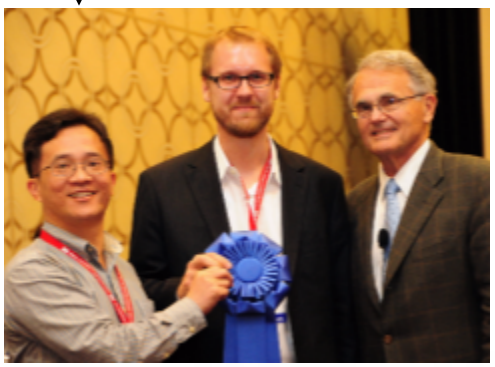

**03/01/2009**
Nanosys achieves >92% QY and <34nm FWHM for both red and green CdSe dots

**2H/2011**
Nanosys ships products for qualification to all leading consumer electronics OEMs

**05/2012**
QDEF named SID Component of the Year

2001- 2009 | 2010 | 2011 | 2012 | 2013 | 2014+

**01/2011**
LG's QD BLU wins Enabling Technology CES Award for their QuantumRail Component



**05/2011**
Awarded Best-in-Show for QDEF-enhanced 47" TV at SID 2011

**10/2013**
Large volume commercial displays launched using QDEF



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# Lessons Learned

- Bringing QD materials to display or lighting markets requires a component solution to be developed for those materials
  - Material integration into components is a multi-year process that transcends QD material science
    - Compatible matrix materials and packaging solutions, which provide high yield and the durability for customer lifetime requirements, as well as customer form factors and other constraints, must be developed
    - Long qualification cycles that include development and proof of accelerated life test models. This means verifying 1x conditions as well, which translates to more than 10,000 hours of material and device testing.
- All of this must be done while providing an energy efficiency and bandwidth (color) improvement over incumbent technologies
- This takes several years to accomplish, even when working with large company partners such as LG and 3M

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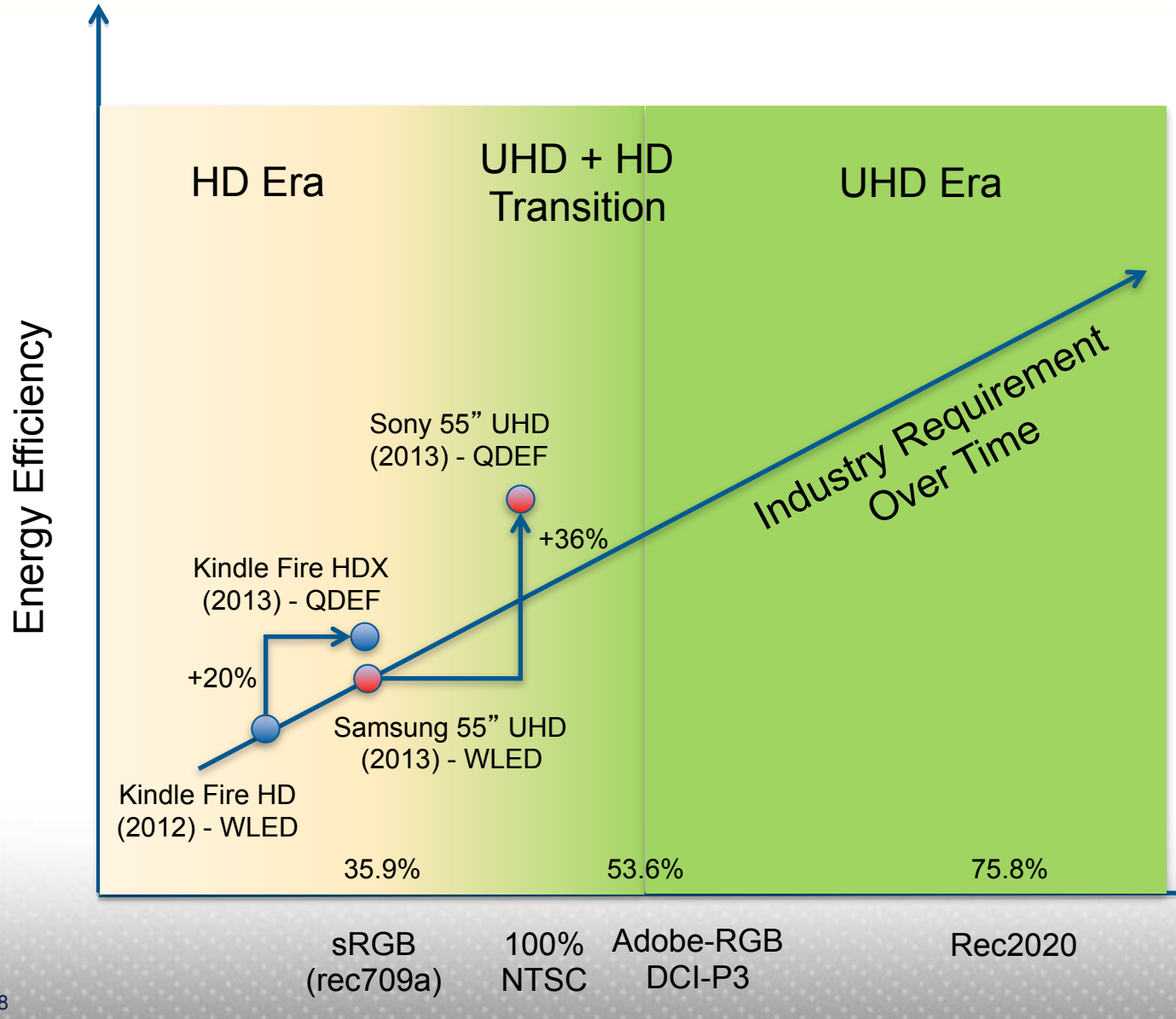
# Color Gamut & Energy Efficiency of Different Display Technologies




As pixels become smaller, aperture ratio and transmission decrease requiring higher efficiency backlighting than what current phosphor technology can deliver

Kindle Fire HD vs Kindle Fire HDX Comparison based on measured display performance of production product

Samsung UHD using WLED vs Sony UHD using QDEF demonstrated and reviewed at IHS Korea, October 2013

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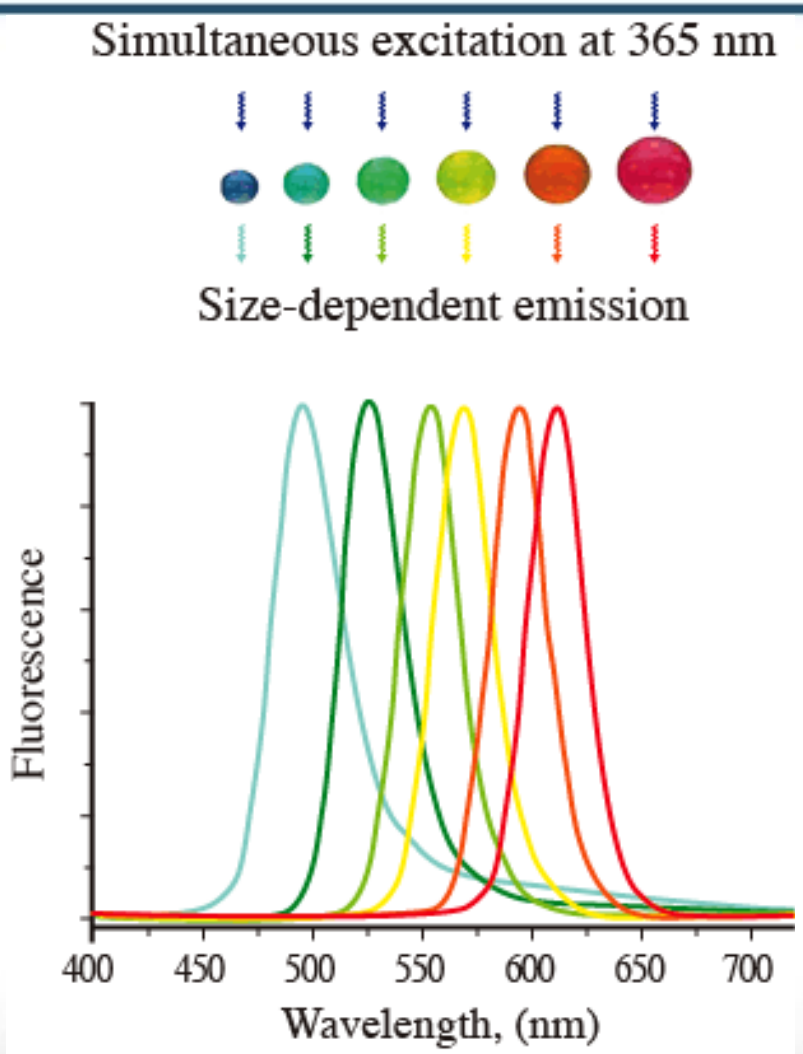
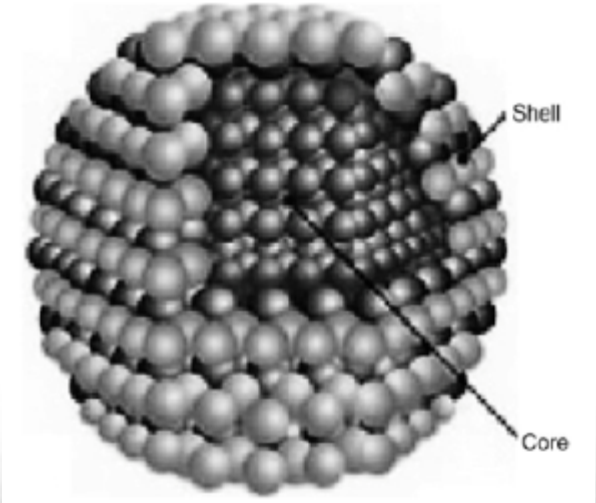
# Core/Shell Quantum Dots




- Narrow FWHM: ~32nm
- Core/shell quantum dots
  - CdSe/ZnS
  - High QY: ~90%
  - Long-term stability
- Developed for 25+ years



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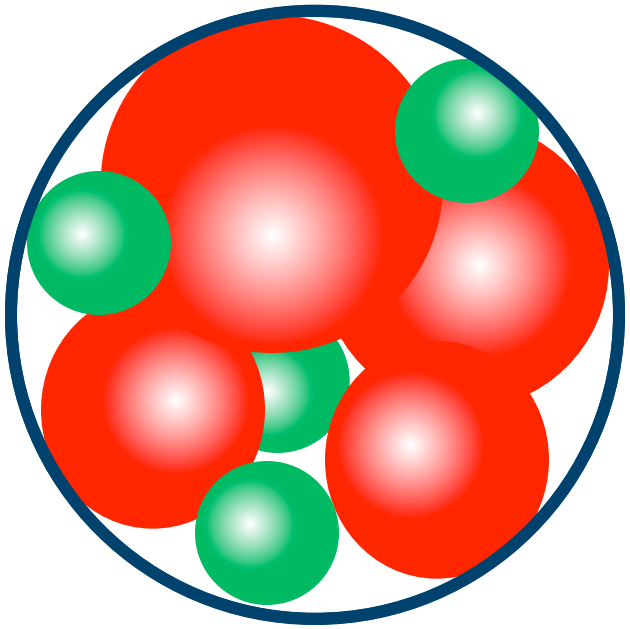
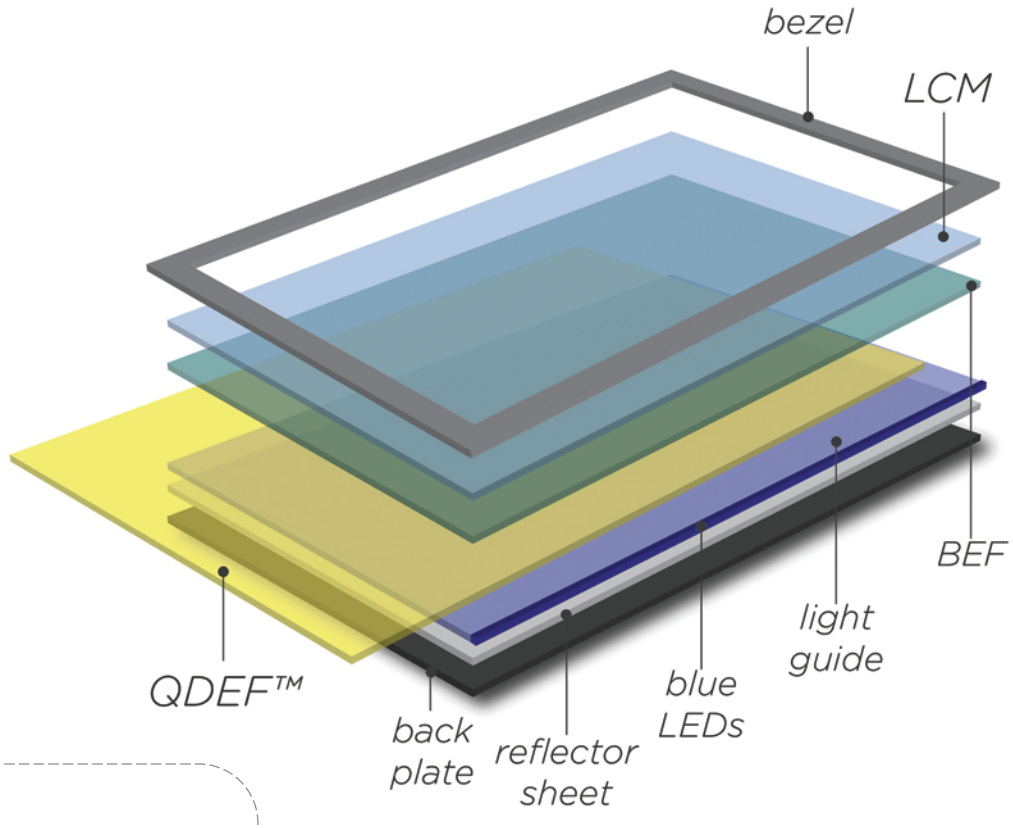
# Quantum Dot Enhancement Film






- QDs embedded in organic polymer
- QD loading in QDEF™ by weight: <0.3%
- Cd concentration <500ppm



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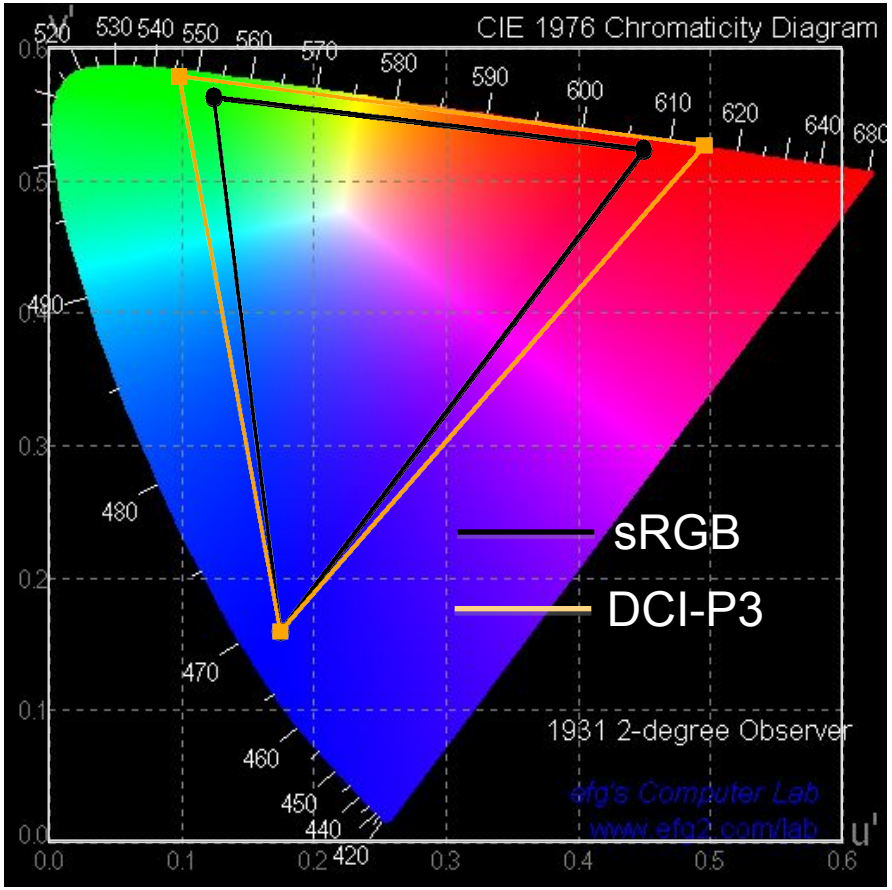
# Colors & Color Gamut




- In displays, the area between the 3 primary color coordinates define the color gamut
- Any color that is inside the triangle can be composed by linear superposition of the 3 primary colors
- Current internet and HDTV color standard is sRGB, which is 72% of NTSC
- Industry is extending displays to higher gamut, ~100% NTSC
  - Adobe-RGB, graphics
  - DCI-P3, digital cinema



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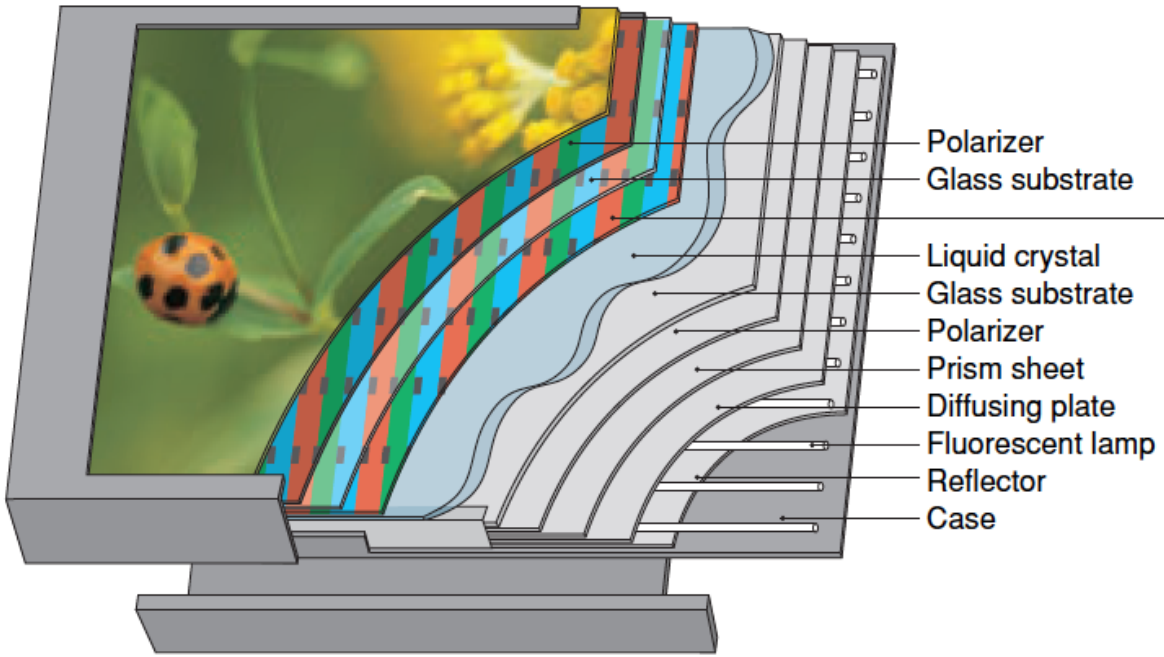
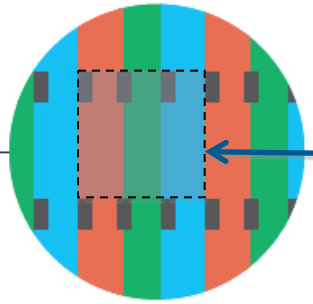
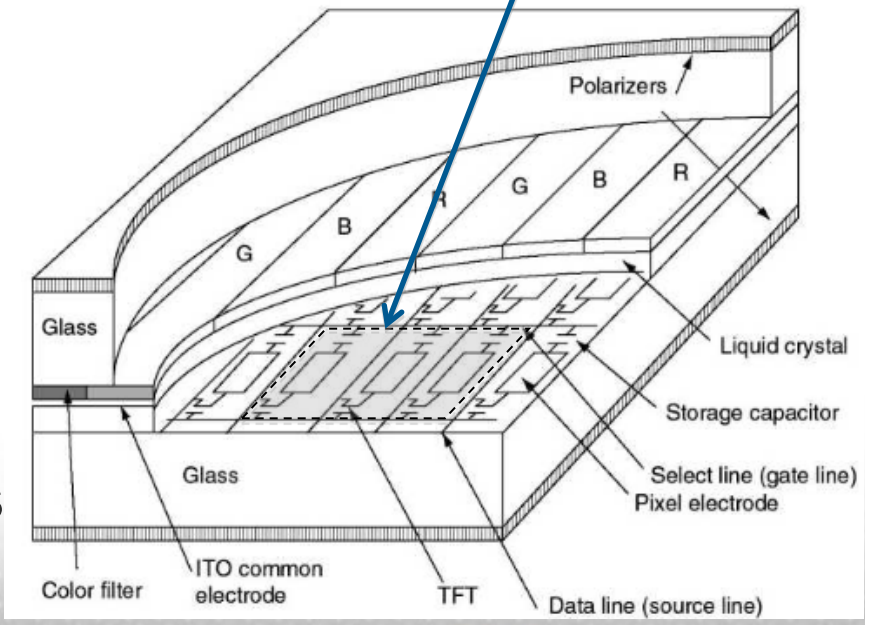
# Creation of Primary Colors in LCD




- In LCD, each pixel consists of R, G, and B sub-pixels
- By using white backlights and color filters, R/G/B primary colors are created



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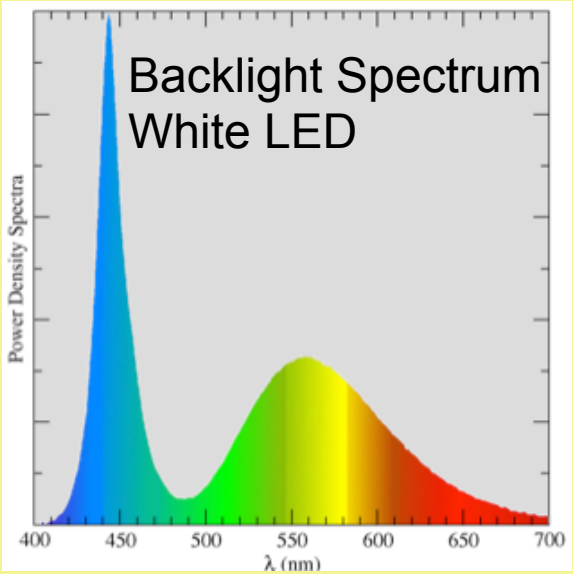
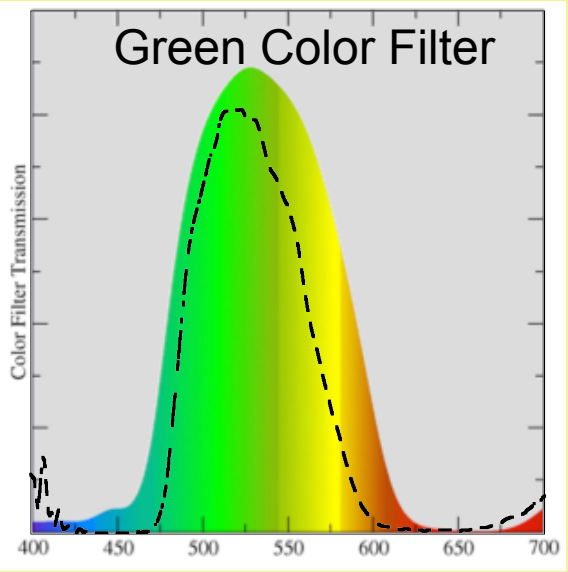
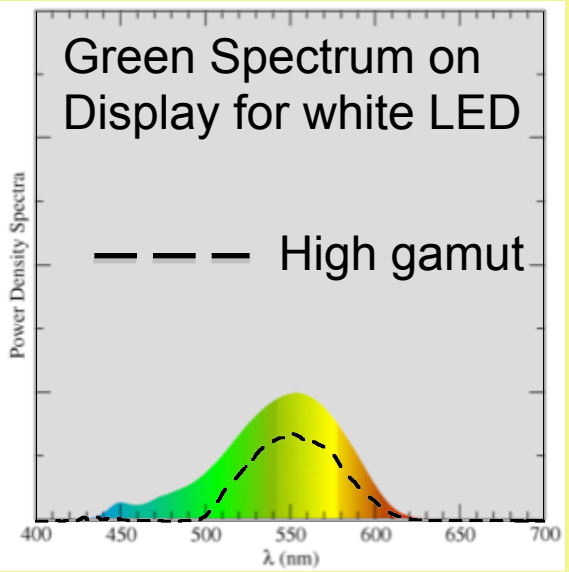
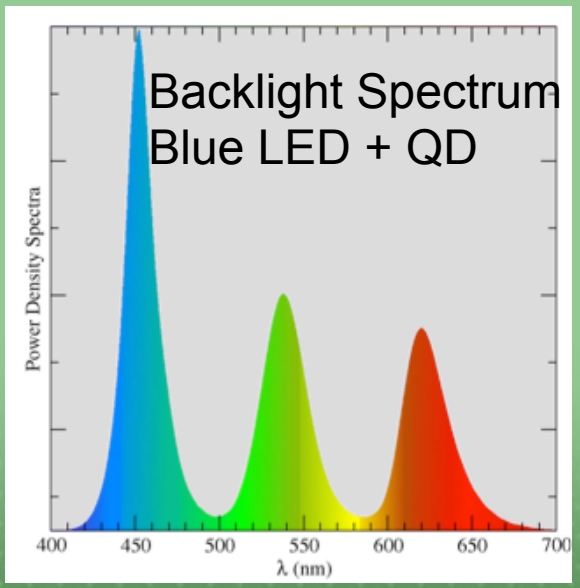
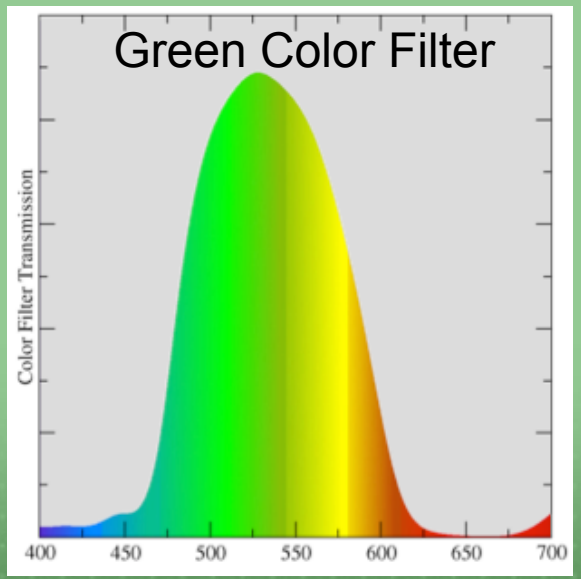
# Impact of Backlight Spectra & Color Filter on Color Purity

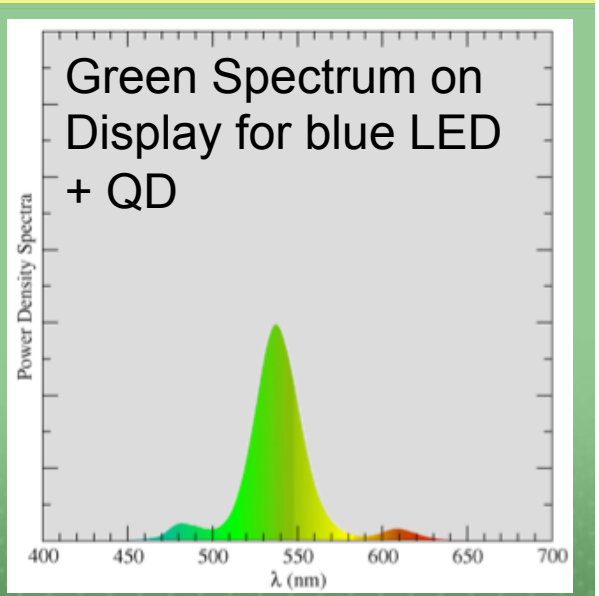


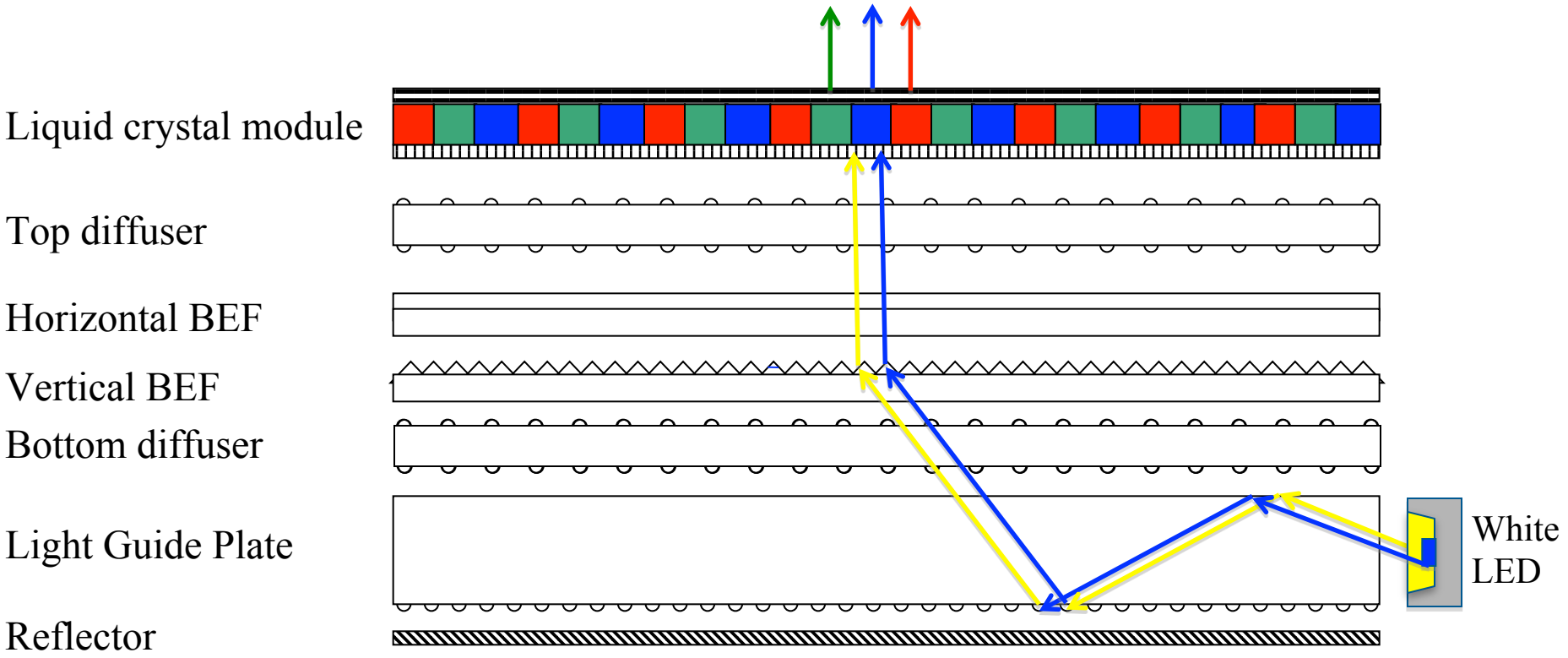



# LCDs with White LEDs as Light Source




- Most of today's backlights for LCDs use white LEDs
- The white LEDs were the most energy efficient backlight sources to-date (prior to quantum dots)



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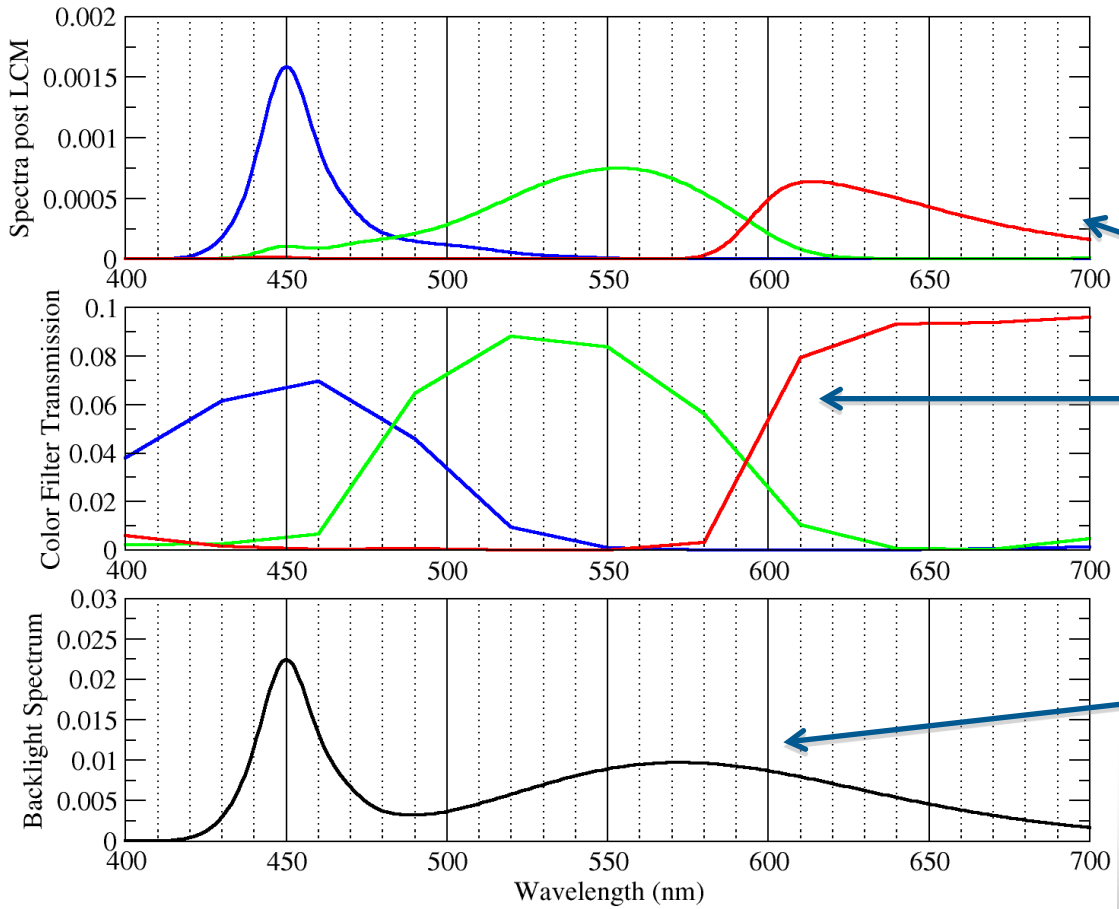
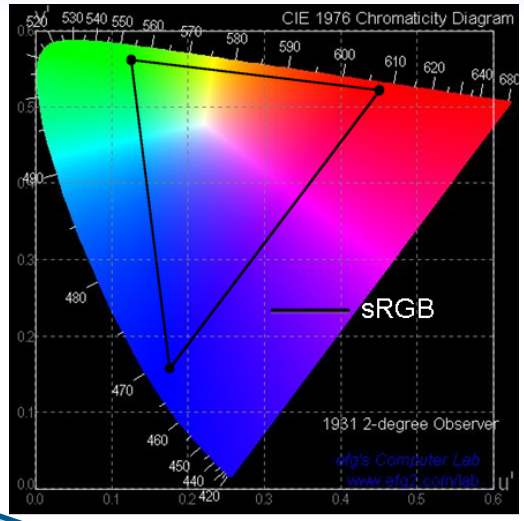
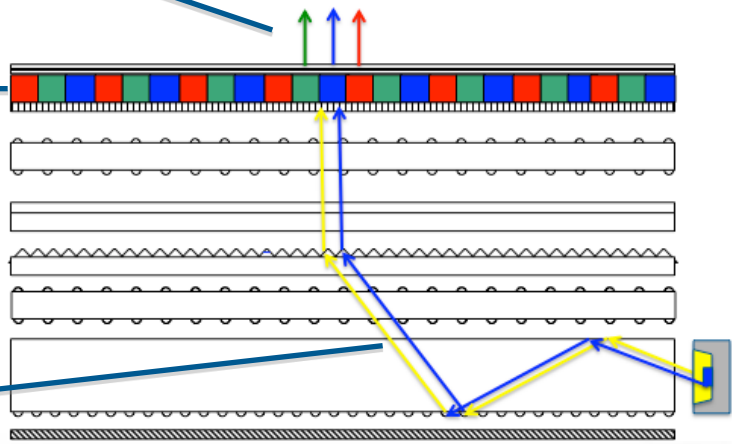
# White LEDs for sRGB Displays





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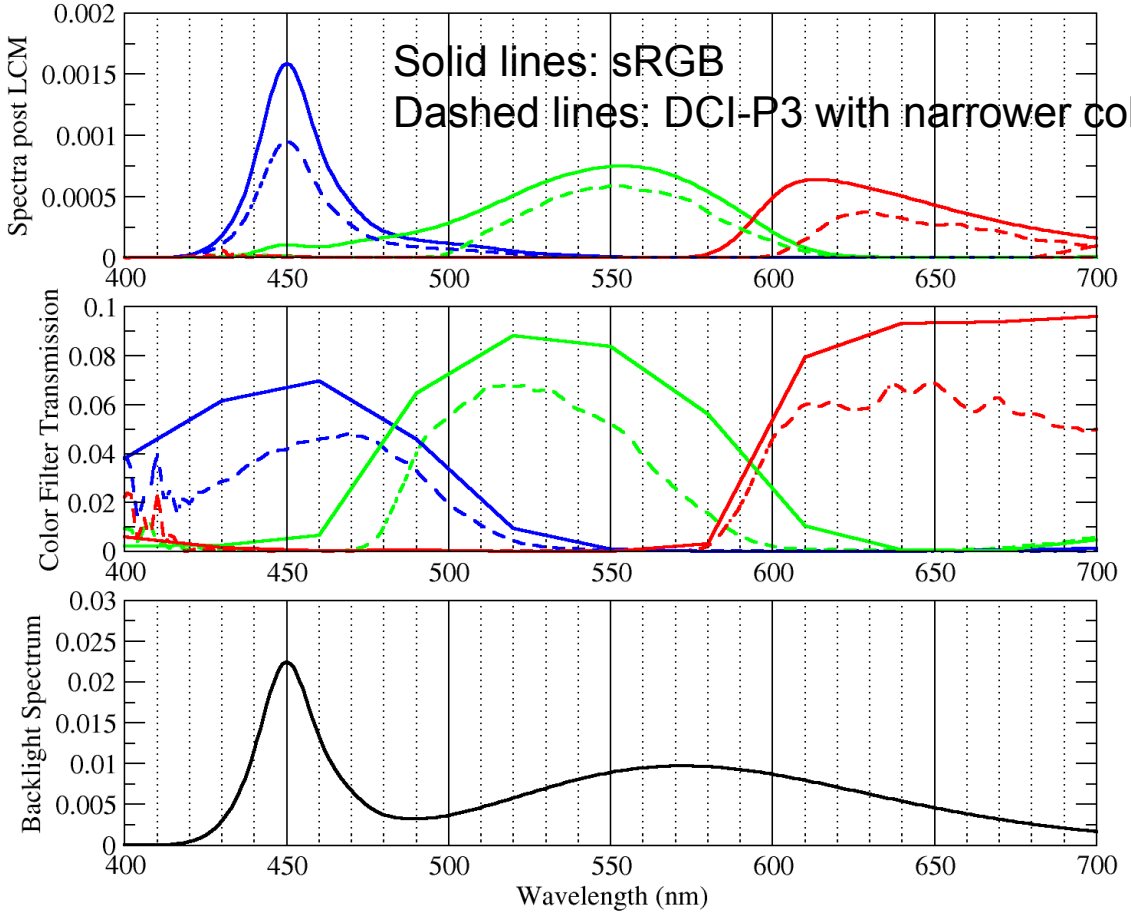
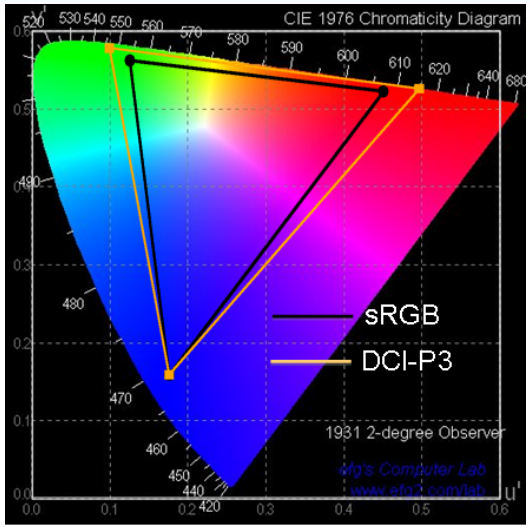
# White LEDs for DCI-P3 Displays




- To achieve 100% NTSC, much narrower color filters need to be used with lower transmission
- **Poor power efficiency with white LEDs for high color gamut displays, ~45% lower efficiency at 100% NTSC**



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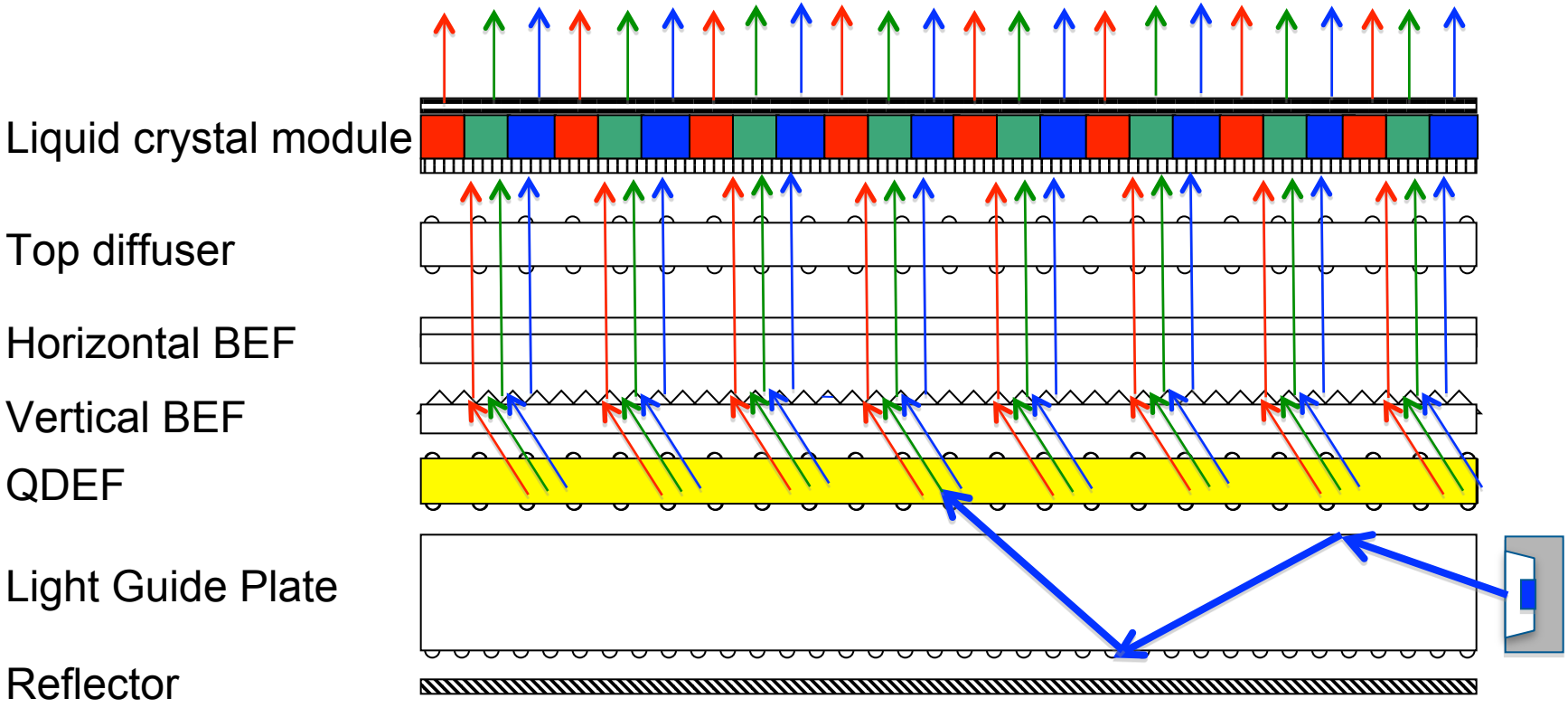
# LCDs with QDEF




- Blue LED replaces white LED
  - GaN-based blue LEDs have highest power efficiency, much higher than OLEDs
- QDEF replaces bottom diffuser: entire display area is illuminated



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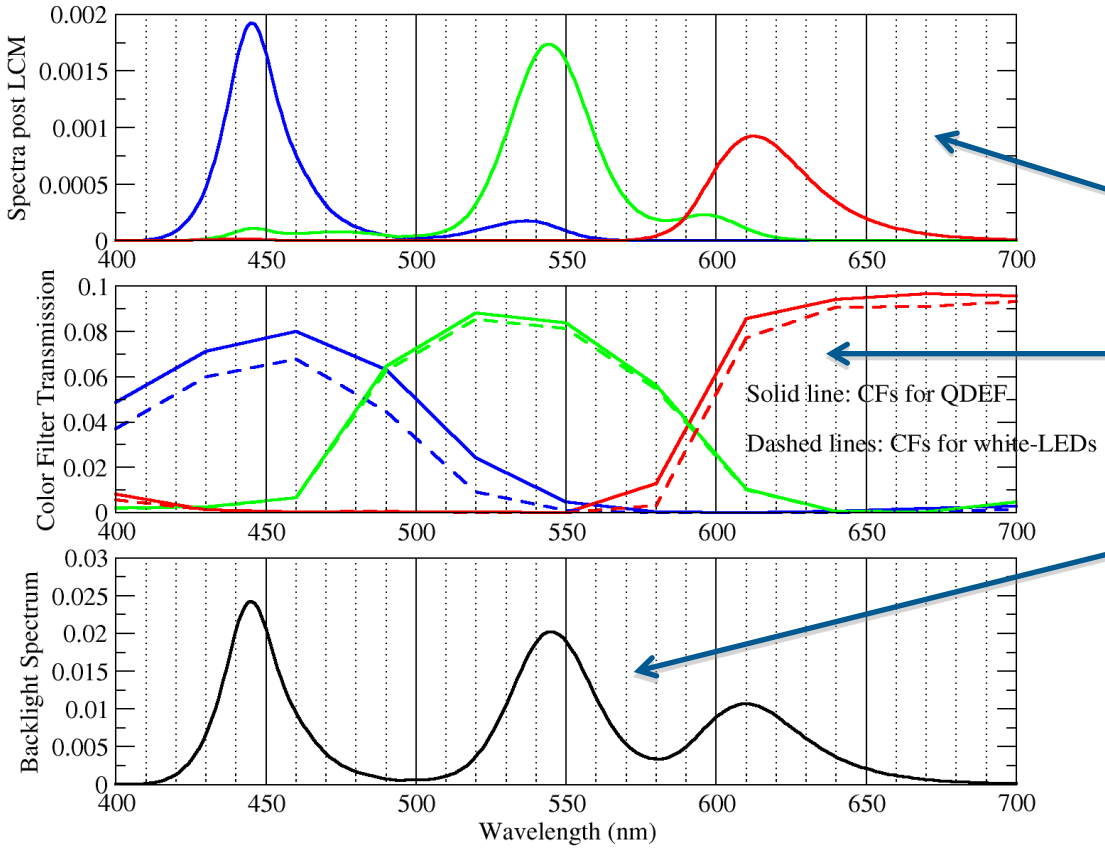
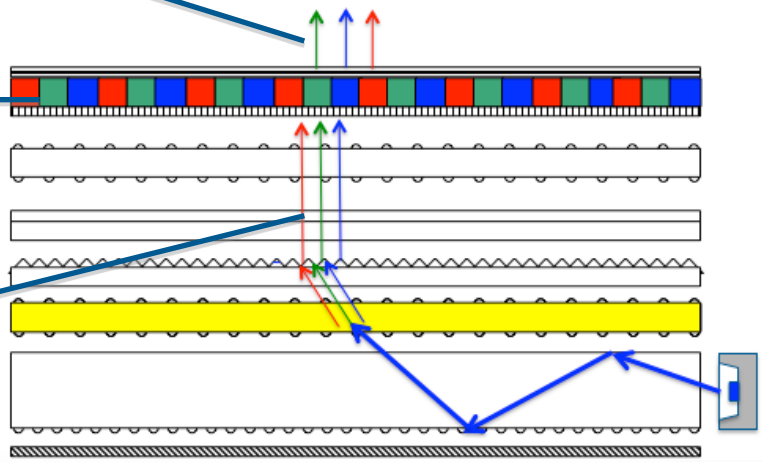
# Higher Power Efficiency LCD using CdSe-Based QDEF for sRGB

- **1st QDEF product used in tablet for sRGB with 20% power efficiency improvement over white-LEDs**





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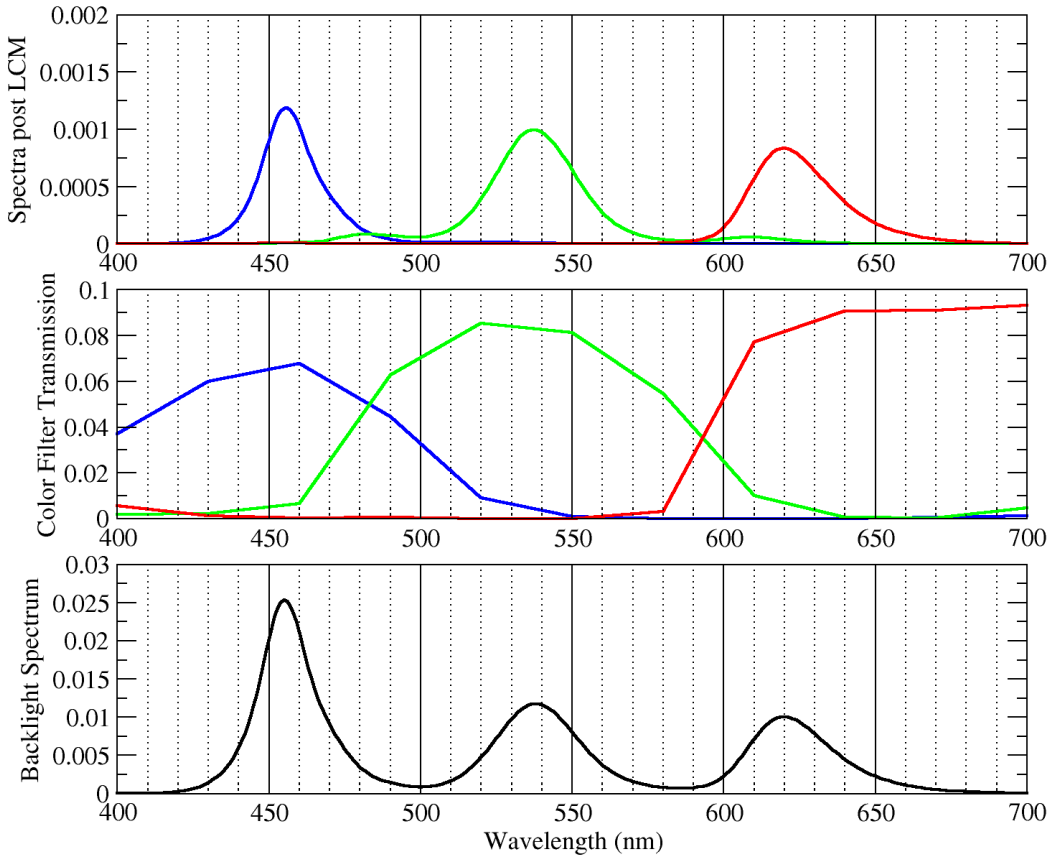
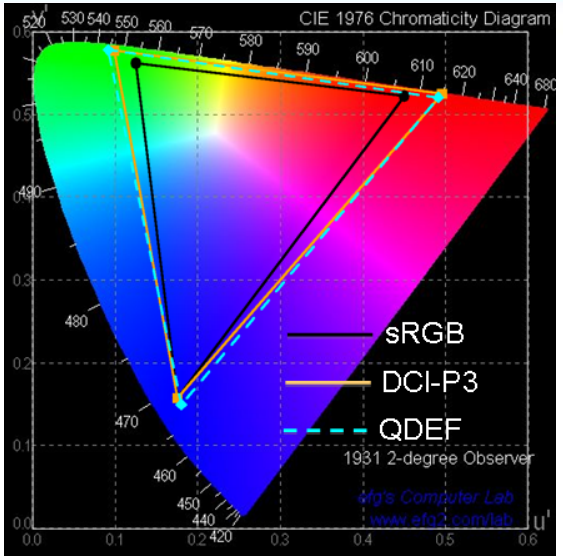
# CdSe-Based QDEF Enables High Efficiency High Gamut LCDs




- QDEFs with narrow green and red line-widths (~32nm) are necessary to achieve >98% DCI-P3 color-space coverage with current CF70 color filters



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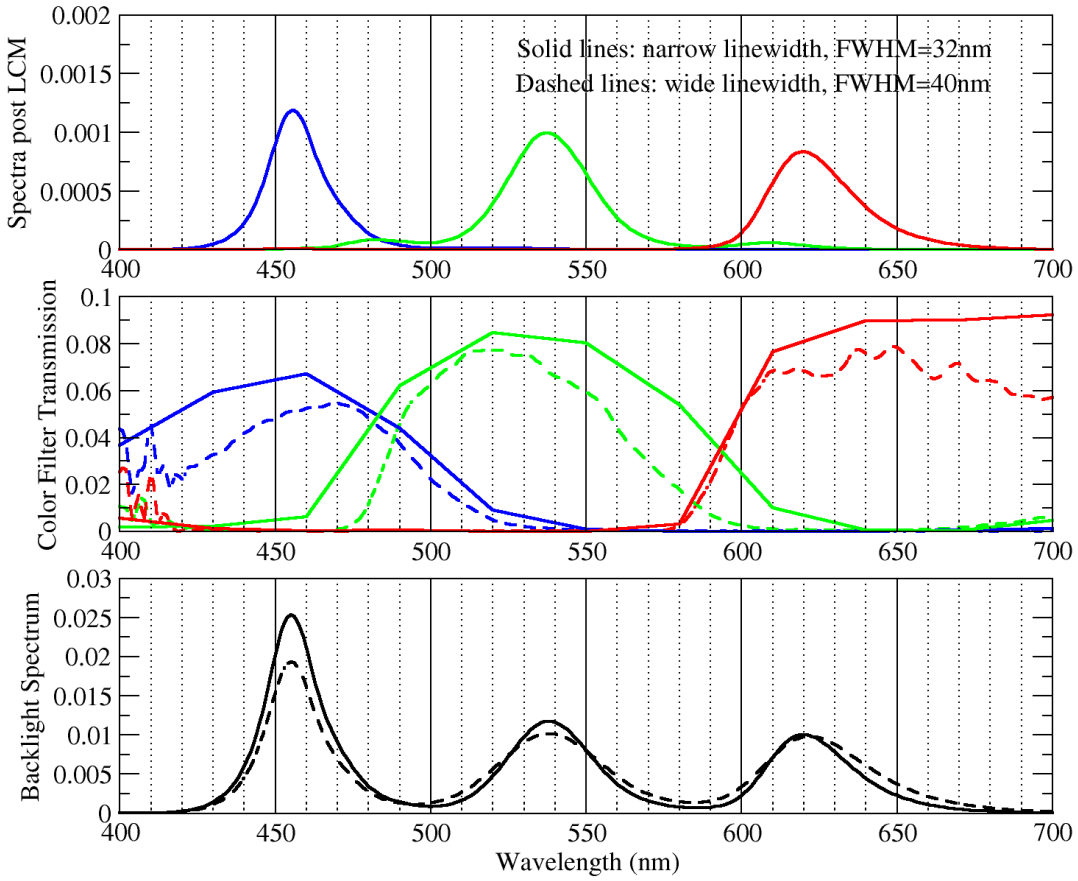
# Impact of Phosphors with Wider Line-Width on High Gamut LCDs




- For phosphors have wider line-width (e.g., current Cd-free QDs), narrower band-pass color filters with lower transmissions need to be used to achieve comparable color gamut
- **10-15% lower power efficiency**



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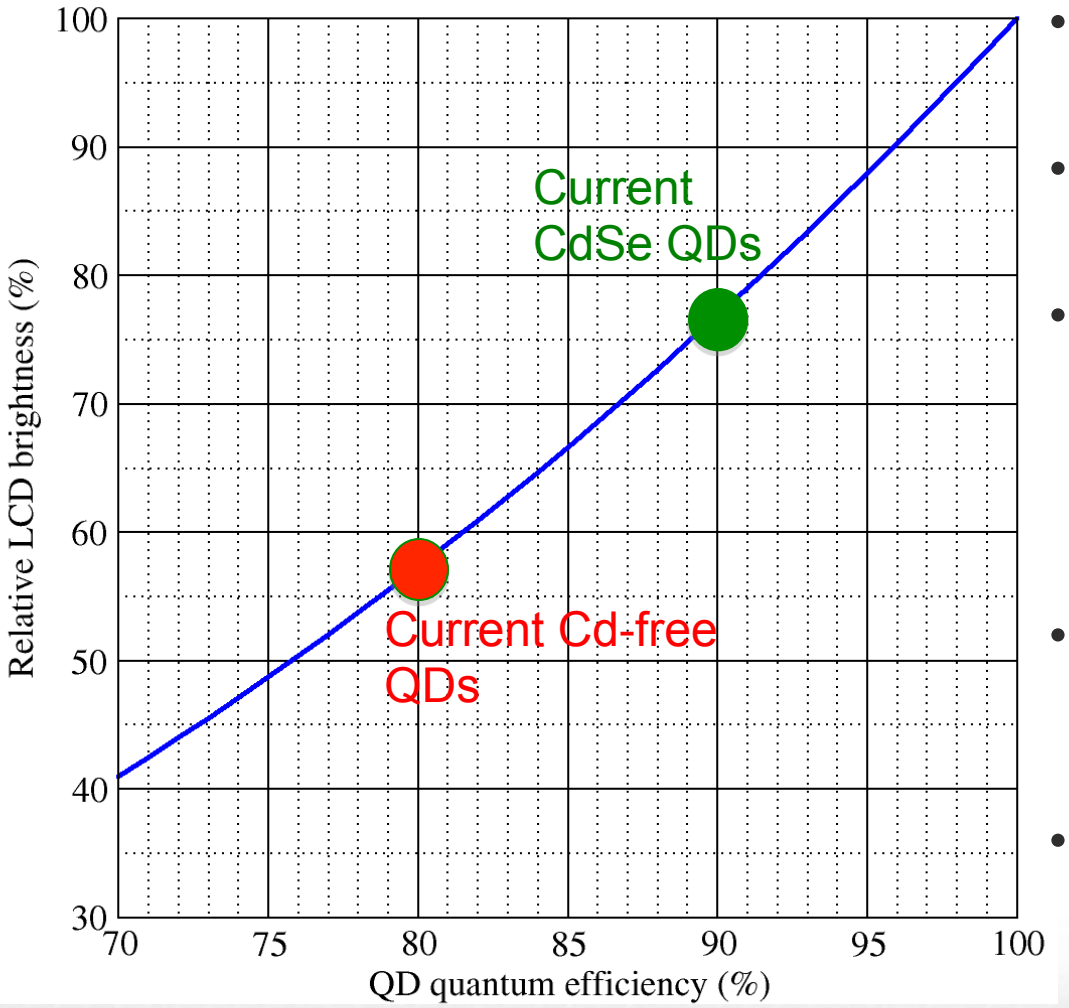
# Impact of QD Quantum Yield on LCD Brightness




- Current CdSe QDs have QY>90%
- Current Cd-free QDs have QY~80%
- As a result of reabsorption (i.e., QDs absorb the photons they emit), the system brightness is nonlinear in QY of QDs
- **With current Cd-free QDs, relative brightness is ~25% lower than CdSe QDs**
- **The combined loss of power efficiency from lower transmission color filters and lower QY is ~35-40%**



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# Power Efficiencies of LCDs with Different Phosphor Technologies

| | | YAG | Current Cd-Free | Current CdSe |
|---|---|---|---|---|
| sRGB | 72% NTSC | 100% | 90% | 120% |
| Adobe-RGB/ DCI-P3 | 100% NTSC | 55% | 60% | 95% |

- Currently, CdSe QDs are the only phosphor material to improve power efficiency of sRGB displays
- QDEF with CdSe QDs can enable high color gamut displays with comparable power requirements as current standard color gamut products

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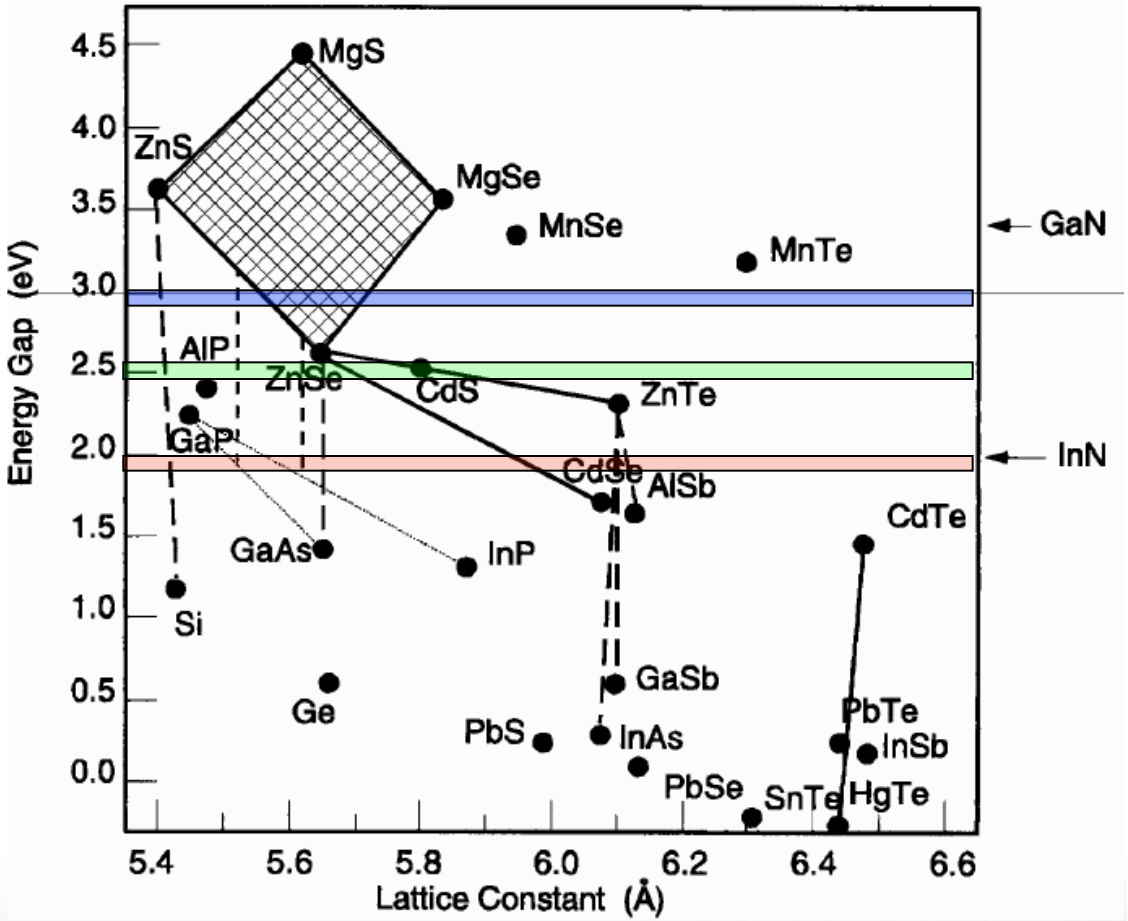
# Materials Choices for Quantum Dots

- Very limited semiconductor materials choices for efficient light emission in the visible
  - Bulk material emission in near IR
  - Direct band-gap
- Candidates for QD core
  - CdSe
  - GaAs
  - InP (In-based)



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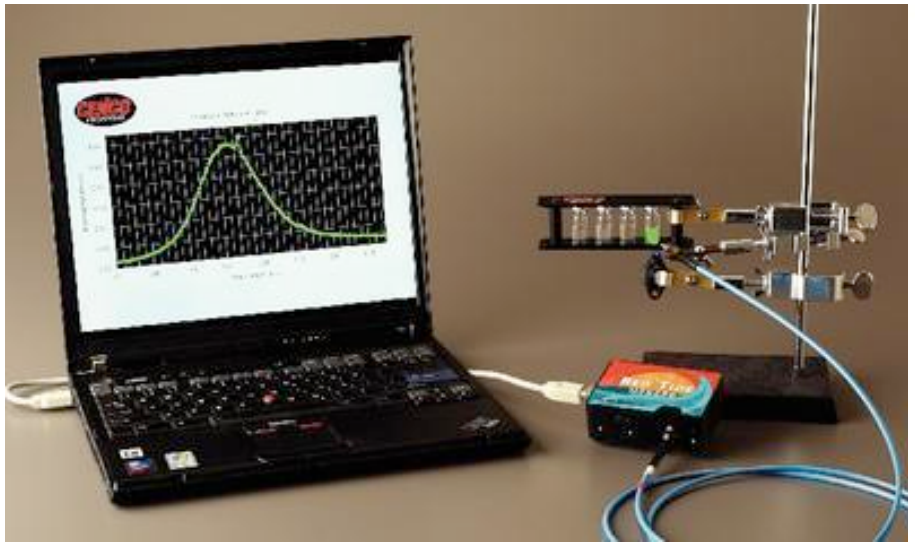
# Nanosys InP QD Development History

- InP quantum dot development started in 2003 for 3rd-generation solar cell
- In 2006, developed In/ZnS core/shell quantum dots for US DOE grant for solid state lighting applications
  - Achieved QY=65%
- Developed education kit with InP/ZnS QDs in 2006, distributed by VWR
- Nanosys has been continuing extensive R&D on InP-based QD
- Customer feedback: Nanosys InP QDs have the best performance among non-Cd QDs samples



- **Granting RoHS Cd-QD exemption will allow a quantum dot industry to develop and for companies including Nanosys to generate revenue from existing Cd-QD technology to produce funding for InP QD R&D activities and bring non-Cd solutions to market sooner**



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# Challenges for InP QDs

- Larger spectral line-width: ≥40nm
- Lower quantum efficiency: ≤80%
- Ligand/polymer system & packaging solutions need development to achieve required performance & reliability
  - Photo-induced degradation
  - High Temperature
  - High humidity
  - Edge-ingress of $O_2$ & $H_2O$ that can bleach out QDs
- Anticipate ~3-5 years, with technology breakthroughs, for InP to achieve current CdSe QD performance and lifetimes

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# The most efficient backlight technology

| 55 4K TV Brightness Demonstration | Samsung 55” 4K WLED | Sony 4K QDEF | Ratio: QDEF/ White-LED |
|---|---|---|---|
| Average Brightness (nits) | 446 | 508 | 114% |
| BLU Power (W) | 136 | 113 | 83% |
| Color gamut (NTSC) | 72% | 100% | 139% |

- Demonstrated and reviewed at IHS Korea, October 2013
- Compared to conventional white LED-BLU in UHD TV, QDEF offers both higher color gamut and power savings
  - 39% higher color gamut demonstrated
  - 36% lower BLU power at the same brightness



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# How much energy could QDEF save?

- Assuming reasonable adoption rates across the US installed base of 130 million LCD TV, 40 million LCD laptop and 40 million LCD desktop displays, this 36% power savings could have a dramatic effect on US energy use by 2020:
  - 9.2 TWh less energy consumed per year
  - 3.7 million tons less coal burned per year
  - 109 billion cubic feet less natural gas burned per year

# Conclusions

- Cd-based QDs are the only material today that can provide high energy efficiency LCDs. In particular, it is the enabling technology for high color gamut displays (e.g., Adobe-RGB, DCI-P3, etc.), which are the standards for UHD with high energy efficiency

- Cd-free QDs, e.g., InP-based QDs, are lagging behind QD-based QDs in performance (lower quantum yield, wider line-width) and reliability. Will likely take ~3-5 years for Cd-free QDs to mature

- By allowing the adoption of CdSe-based QDEF, significant energy savings can be achieved for LCD displays, especially TVs, that leads to a large positive impact on the environment. In addition, a viable QD industry will develop leading to more research money flowing into development of Cd-free QDs.

*Thank You!*



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