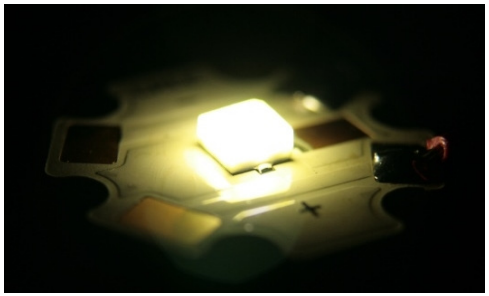
Pacific Light Technologies

On-Chip Quantum Dots for
Better Color Performance & Higher Efficiency



Outline

- PLT Intro
- QDs and Market Opportunity
- PLT Advantage and Latest Improvements
- Cd-free QDs

PLT Company Overview

- Established in 2011 in Portland OR
- World class R&D team
  - 6 PhDs, 8 MS
- Outsourced manufacturing
  - Capital efficient
  - Leverages existing chemical manufacturing org

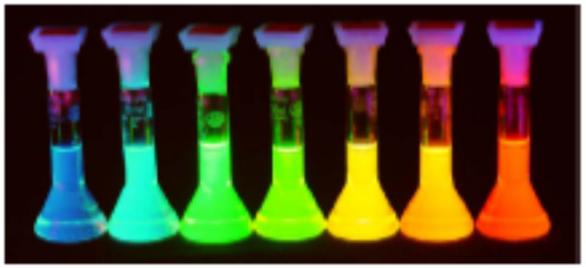
- Funding

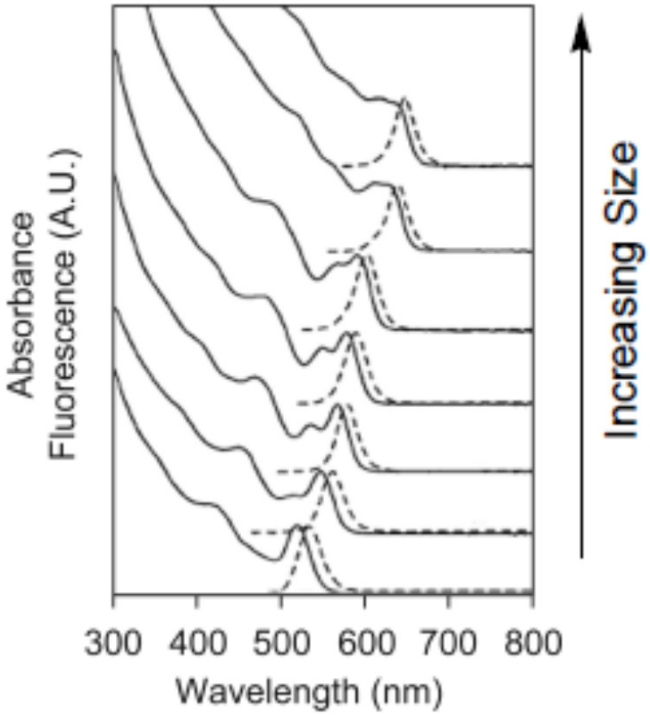
  - ~$10M venture funding to date
  - JDA funded product development
- Strong engagements with industry leading companies in lighting and display

PLT Team

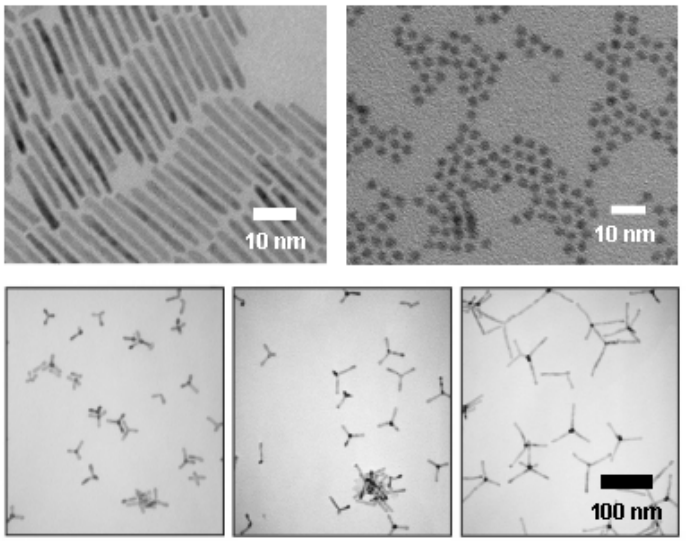
- Doug Barnes – President and CEO
  - 35 years industry experience, 20 years in executive leadership roles
  - COO at NanoH2O 2012-14, 25 years at Planar Systems, Inc. GM of $120M P/L, VP Global Operations with deep Asia relationships
  - BS Industrial Engineering, Stanford University
- Dr. Juanita Kurtin – Founder, Chief Technical Officer
  - Founded Pacific Light Technologies and Spectra Watt, and 8 years at Intel
  - Broad background in nanomaterials research with focus on quantum dots.
  - BS Chemistry from the MIT, Ph.D. Physical Chemistry from the UC Berkeley, studying with quantum dot pioneer Dr. Paul Alivisatos.
- Dr. Norbert Puetz – Vice President of Engineering
  - 30 years technology leadership experience , with focus in compound semiconductor technologies
  - Positions include Cyrium Technologies, quantum dot for solar, Agility Communications (acquired by JDSU in 2005), Bookham, Nortel, Bell-Northern Research
  - Ph.D. in Semiconductor Technology from the University of Aachen (RWTH), Germany.
- Heather Deibele – Director of Manufacturing
  - 15 years operational leadership experience in commercialization of technologies in chemical and pharmaceutical industries
  - BS Chemical Engineering, Oregon State University; MBA from University of Oregon

Semiconductor Quantum Dots

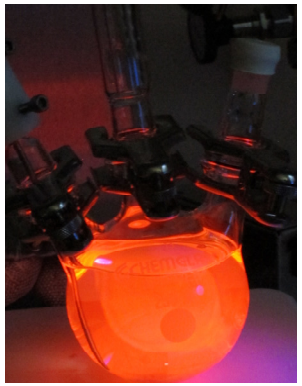




CdS, CdSe, CdTe

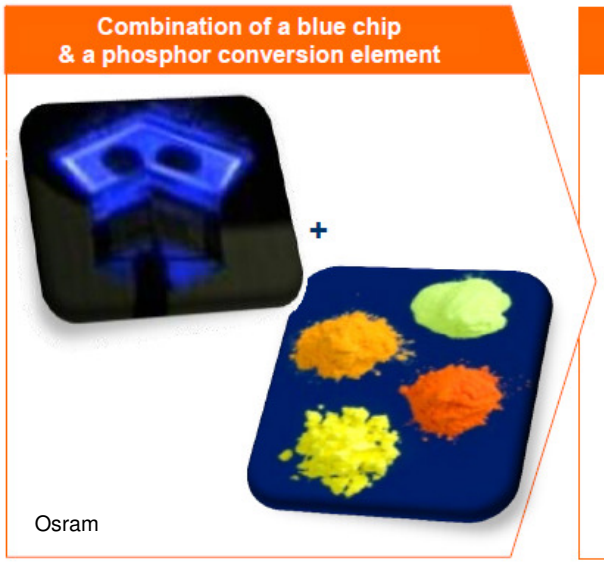


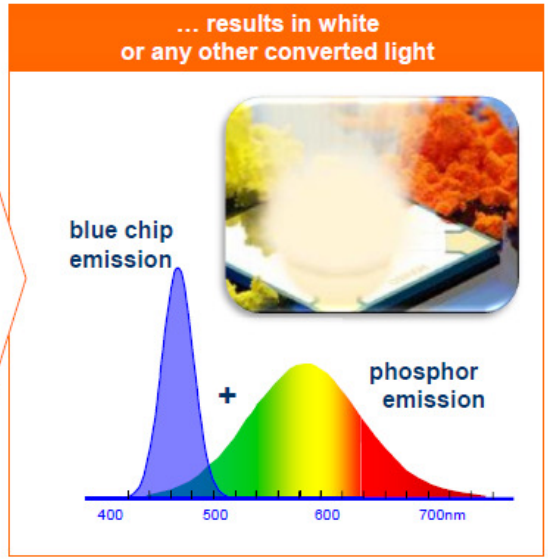
Murray, C. B.; Norris, D. J.; Bawendi, M. G. *JACS*, **1993**, 115, 8706
Alivisatos, A. P. *Nature Materials* **2003**, 2, 382



Optical properties controlled by size, materials, & shape

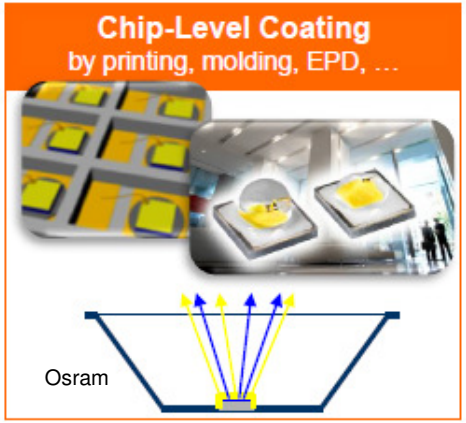
Phosphor-converted LEDs

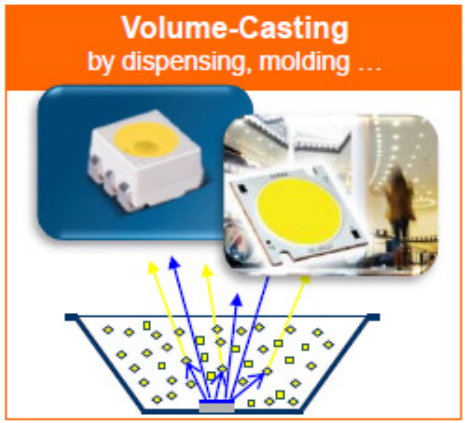


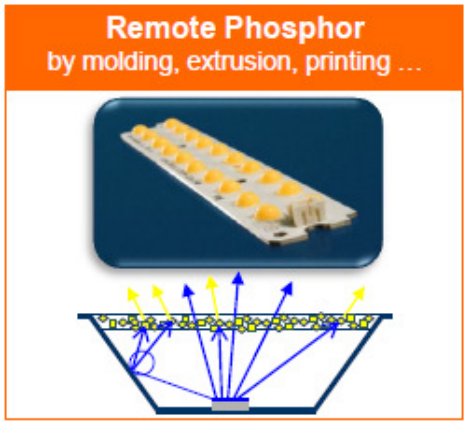


Phosphor Disadvantages

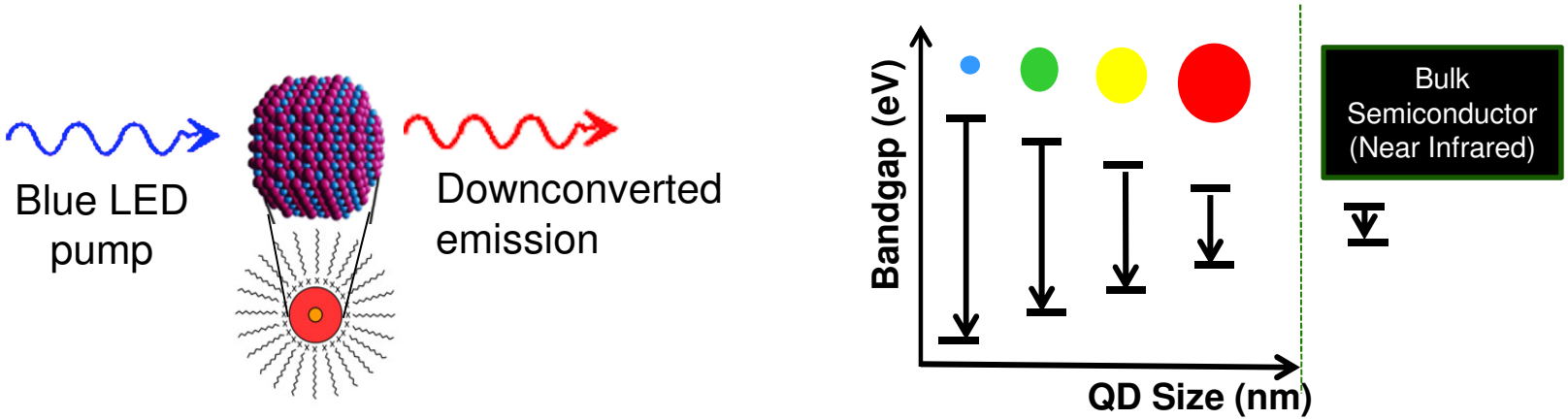
- Wasted Energy
- Broad Spectrum/Difficult To Adjust "Color Quality"
- Poor overlap of Absorption w/Blue pump
- Variation ➔ Binning Losses







QD Downconverters—The Ideal Phosphor



- *High absorption at the blue pump wavelength*
- *Precise peak emission placement (± 1 nm)*
- *Fast excited state lifetimes—prevents saturation*
- *Very narrow emission spectra (<35 nm FWHM)*
- *Very high efficiencies (>90%)*

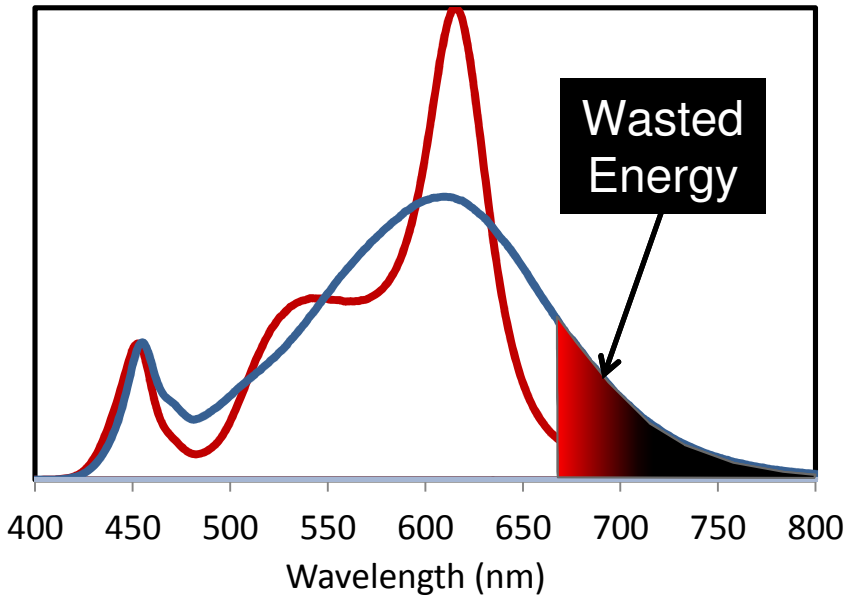
QD Market Opportunity

- Lighting and Displays are both significant market opportunities enabled by LEDs
  - LED backlit (direct and edge-lit) displays and solid state illumination
- Quantum Dots provide the next wave of advantages
  - Broad color gamut
  - Up to 30% efficiency increases

- QD adoption barrier: ***System complexity***
  - QDs in film – adds cost and assembly thickness
  - QDs in glass rods – adds costs and limited to edge lit backlights
  - Lighting cannot use quantum dot films or glass rod solutions – **only solution is quantum dots on-chip!!**
- PLT solves the QD complexity problem for BOTH lighting and displays

Illumination Opportunity

QDs Increase Efficacy and Improve Color Quality



At 90 CRI, CE increases by ~27% by replacing standard red phosphor with red QD

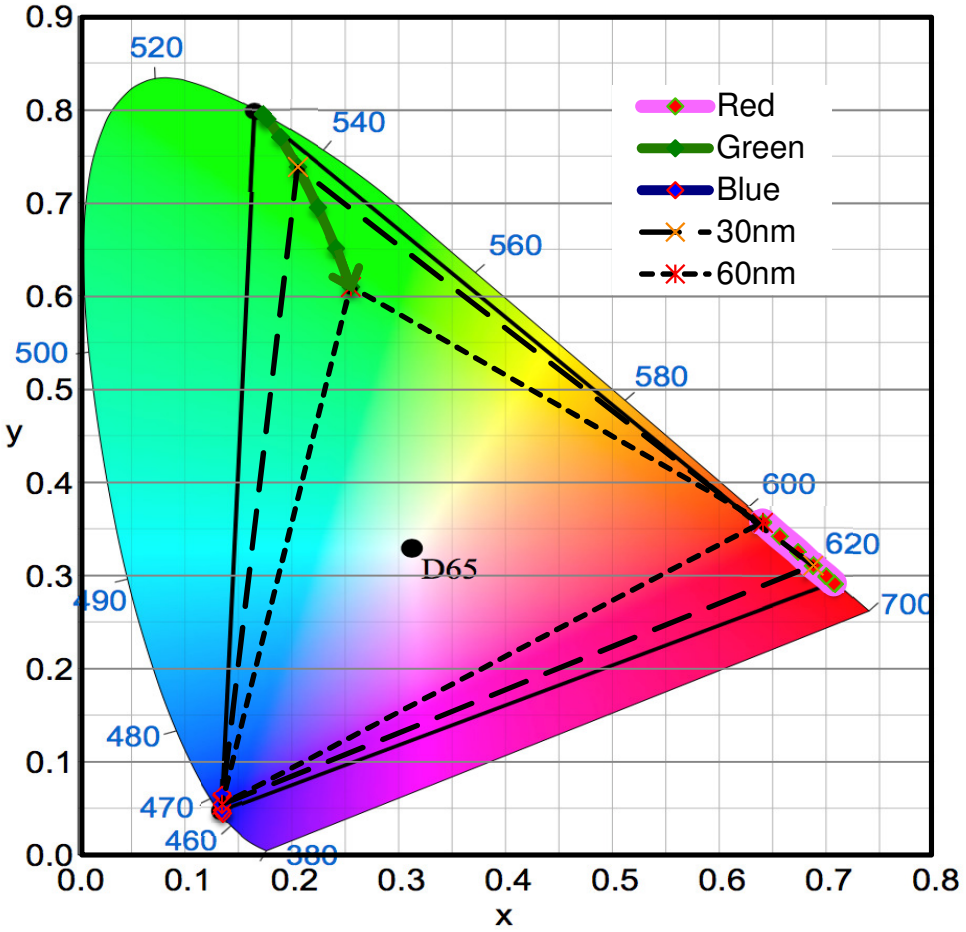
On-chip QDs are the only QDs that can go into lighting:

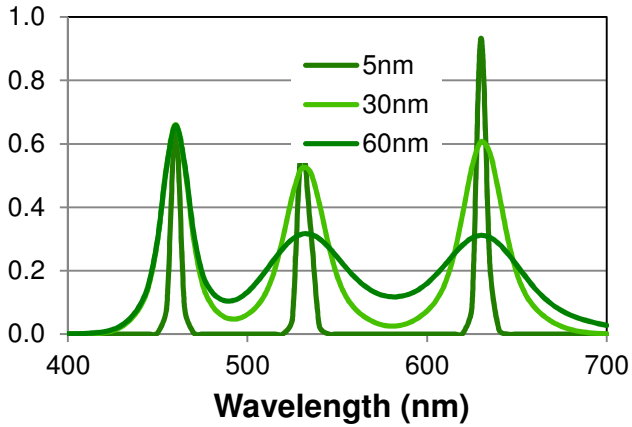
- Cost effective architecture
- Small source size

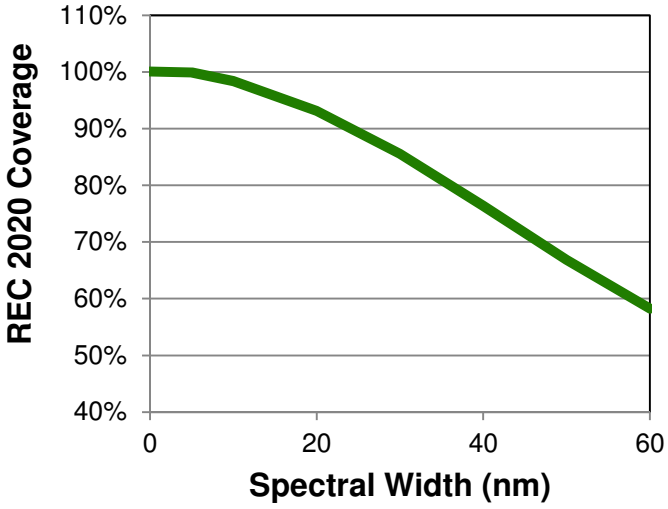
Wide Color Gamuts Require Narrow Spectral Widths

…play to quantum dots' strengths

Rec. 2020 example







Gamut coverage drops off substantially as spectral width of primaries increases

Quantum Dot TV Buzz at CES 2015

Quantum Dot Technology Market Validation!!

Quantum Dots Make a Scene at the 2015 CES

Will we be saying, 'dot's nice' in the future? TVTechnology Now featuring content from Broadcast Engineering BOB KOVACS / BROADCAST ENGINEERING EXTRA 01.16.2015 11:00 AM

LG to launch 'quantum dot' TVs at CES 2015

Quantum dot technology will increase the colour reproduction rate in LG's LED TVs by more than 30 per cent The Telegraph By Sophie Curtis 10:49AM GMT 16 Dec 2014

LG's 'quantum dot' TV Photo: LG

Samsung joins the quantum dot crowd at CES 2015 with super SUHD TVs ConsumerReports.org Published: January 05, 2015 01:00 PM

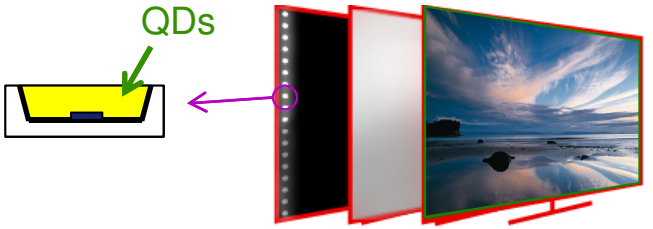
TCL 55" Quantum Dot TV with Color IQ™ Optics Debuts at CES 2015

BusinessWire QD Vision, Inc. January 5, 2015 4:00 PM

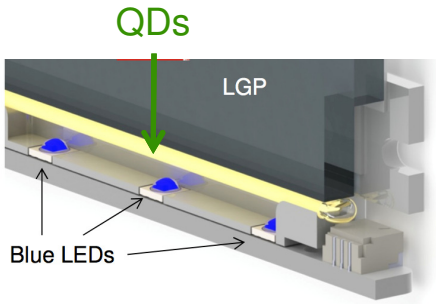
Source: Samsung

Three methods of QD integration

- On-chip:
  - *Drop-in* LED replacement in the system
  - No system re-design required—lowest cost
  - Minimum material quantity requirements (min usage of cadmium)
  - Maximum temp and flux performance demand

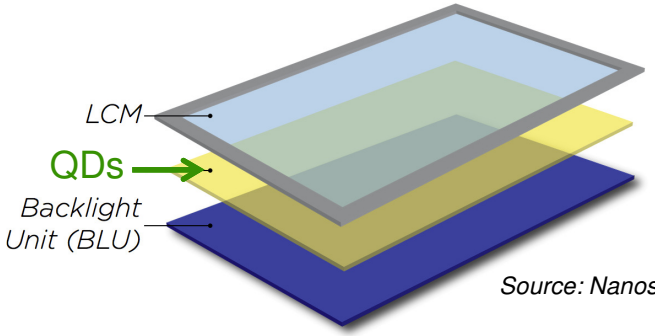


- On-edge:
  - Sealed optic between LEDs and edge-lit BLU
  - Intermediate material and performance demands



Source: QD Vision

- On-surface:
  - Film covers entire screen area
  - Minimum temp and flux performance demand
  - Maximum material quantity required

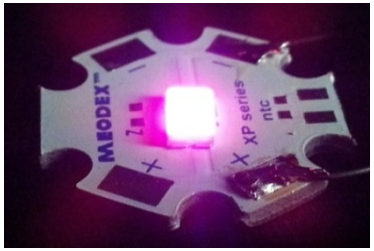


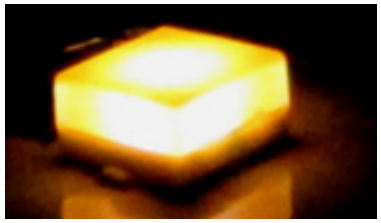
Source: Nanosys

What's Unique about PLT

1. Built-in Protective Layers

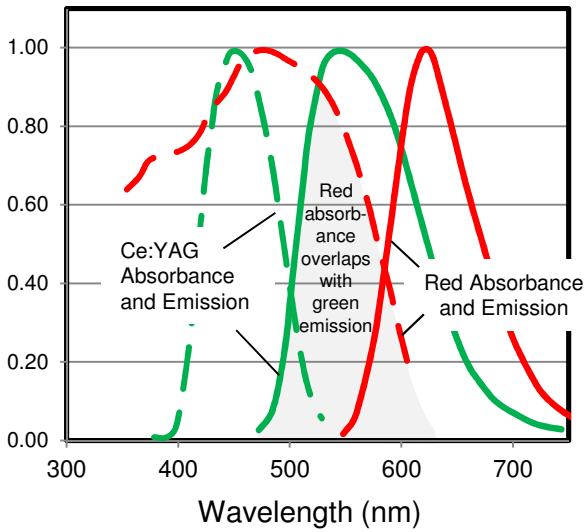
- Tailored for the heat and flux of on-chip environment—phosphor-like stability
- Handled in air like phosphors
- Humidity Resistant
- No external environmental seal required



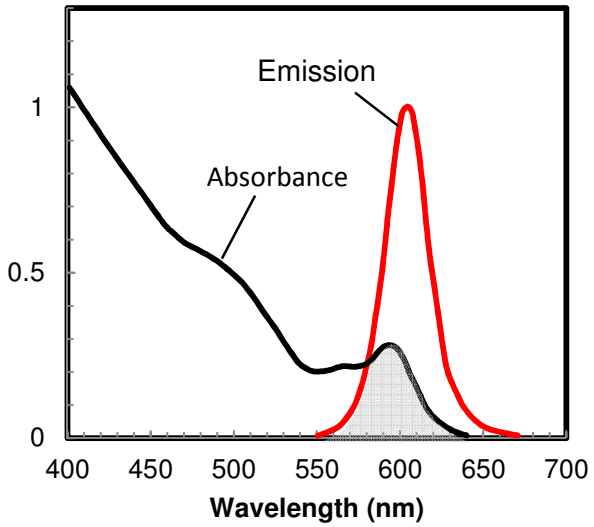


2. Very low self-absorption

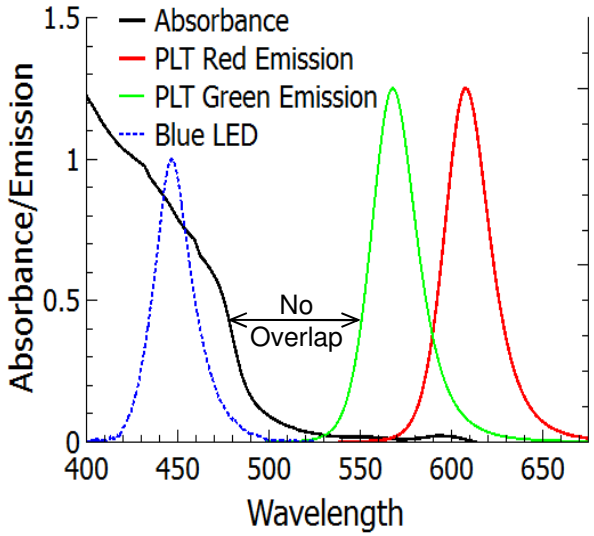
Conventional Phosphors



Conventional Quantum Dots



PLT Quantum Dots



PLT's Gap between absorption and emission enable the high concentration required for on-chip application and color combinations

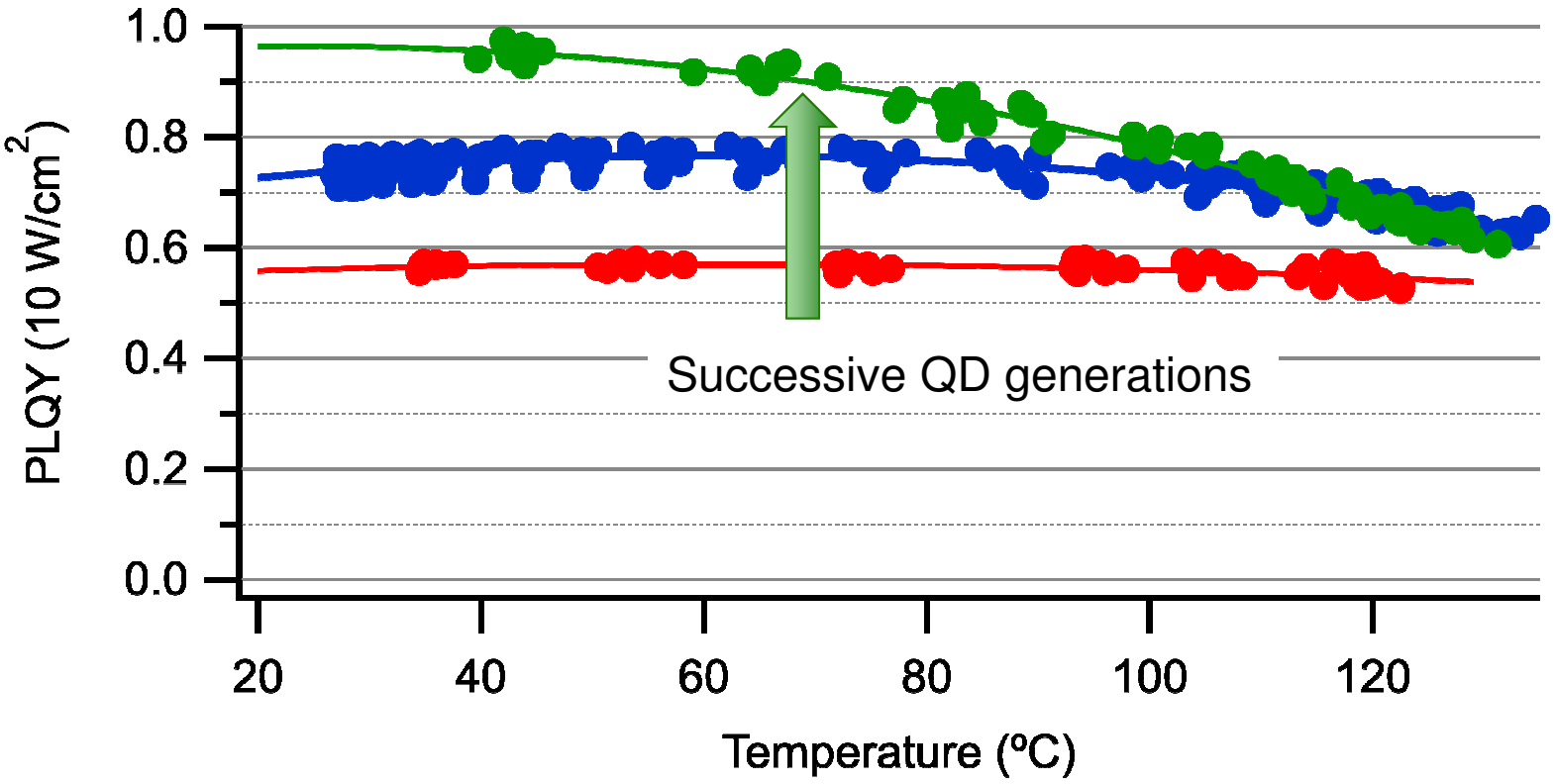
3. Seamless Integration

On-chip: Drop in for ANY white LED

- ***System Level Drop-in*** **LED replacement**
- **No re-design required—QD on the LED Chip!**
- **Minimum QD material (Cd) requirements**
- **Works for *all* size display**
- ***Only*** **QD solution for lighting**

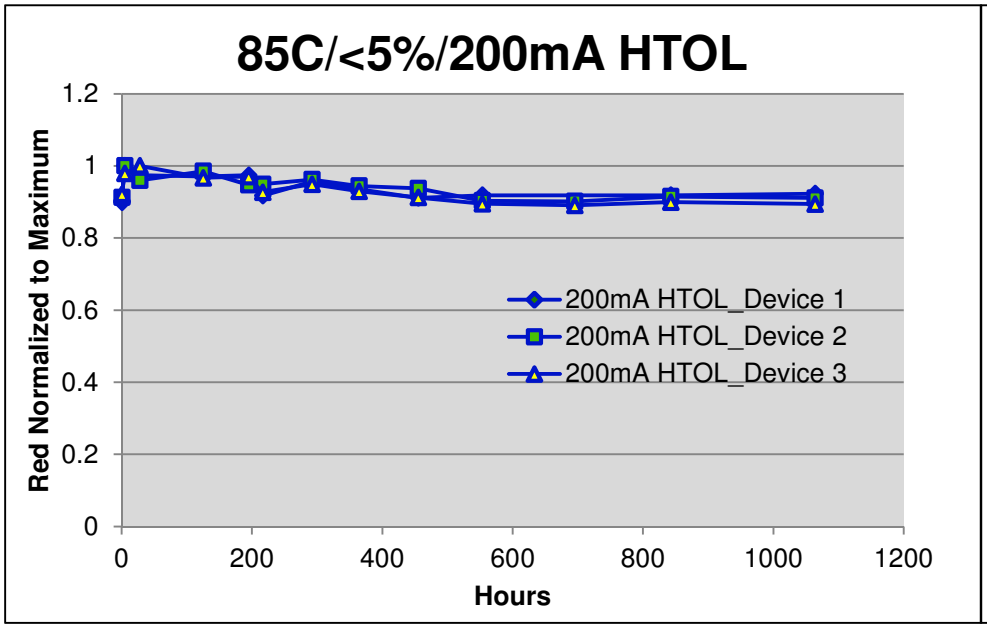
Drop-in replacement for Phosphor

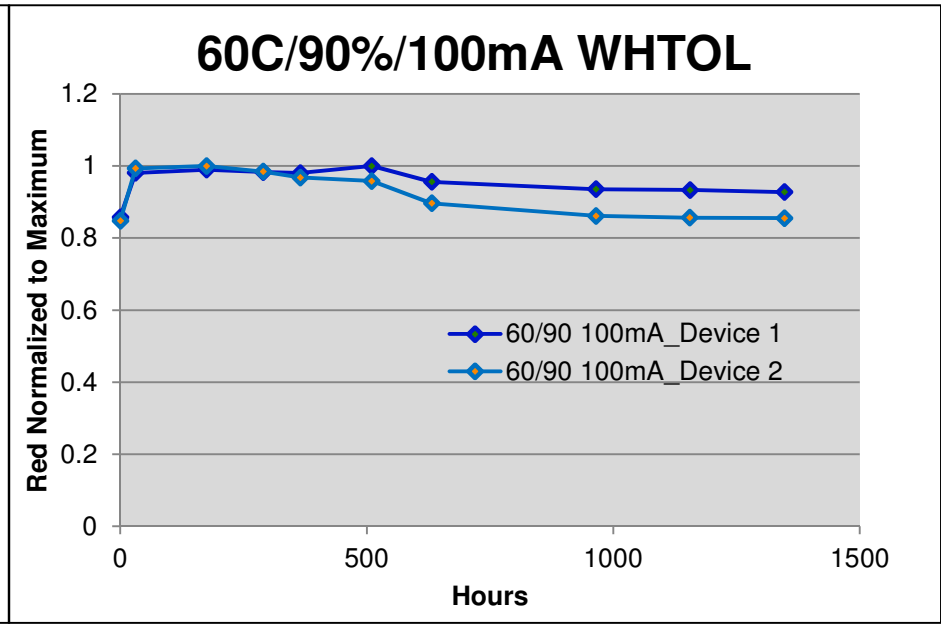
PLQY: Improvements to thermal performance while still meeting reliability requirements

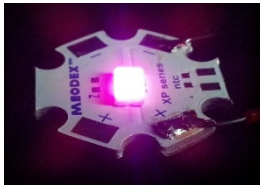


Measured in conventional LED silicone film, no external seal

On-chip reliability: HTOL and WHTOL both meet requirements



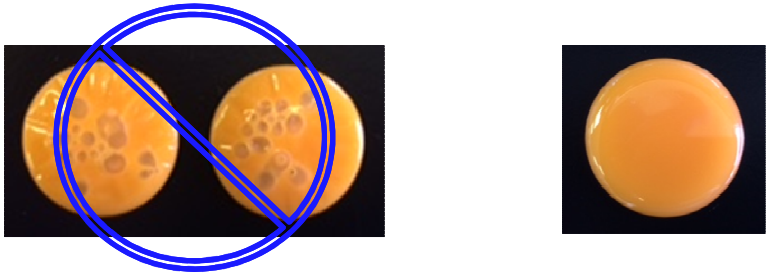




- Red-only pkgs have been aged for >10,000 hrs
- Lifetimes > 25Khrs. possible under use conditions

Other important points for on-chip product

- Compatibility w/wide variety of LED-grade silicones



- Storage and delivery method
  - QDs are typically handled and stored in solvents, standard phosphors are stored as powders
- Minimal modifications to complex LED manufacturing process
- Materials compatible with multiple SMT steps, T> 260ºC for brief periods of time

Advancements in Cd-free QD Materials

- Samsung has recently introduced a TV based on InP nanoparticles
  - Film-based with ultra barrier layers
  - FWHM of 41nm for green, 55nm for red
  - Color gamut of 92% NTSC (vs 102% NTSC coverage from QDVision Cd-based materials)
- A 2013 paper by Osram/Nanoco looked at a variety of Cd-free materials and judged InP to be the closest to market
- Issues with InP:
  - *Stability*: InP is very sensitive to oxygen and moisture
  - *FWHM*: Synthetic process more difficult to control, resulting in broader QD emission linewidth
  - *Efficiency*: Efficiency of InP materials still lower than Cd-based materials

PLT Strategy for Cd-free

- Evaluate Cd-free materials based on their potential to replicate key features of PLT Cd-based QDs
  - Electronic structure and crystal structure compatible w/on-chip QD design
  - Outer semiconductor material system compatible with barrier coating
  - FWHM below 30 nm achievable
  - Materials can be handled in air

Questions?

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