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January 8, 2016

Subject: Input for stakeholder consultation for RoHS exemption requests 2013-2 and 2013-5

Dear Dr. Gensch,

We appreciate the opportunity to provide input on the aforementioned RoHS exemption requests. Further to the various materials so far submitted by others, we would like to provide the attached technical input.

Sincerely,

Charlie Hotz
Vice President Research and Development
Nanosys, Inc.

## CdSe vs InP (Cd-free) Quantum Dot Performance Measurement and Analysis

Submitted by Nanosys, Inc.
January 8, 2015

## Introduction and Methodology

As exemptions to RoHS are granted to narrowly-defined applications for which the elimination of the prohibited substance is technically or scientifically impracticable or when the only available substitution produces more negative than positive benefits to the environment, health, or consumer safety[1], we seek with our input to analytically quantify the difference between the available substitution products and CdSe quantum dots when used in display applications per the exemption requests 2013-2 and 2013-5.

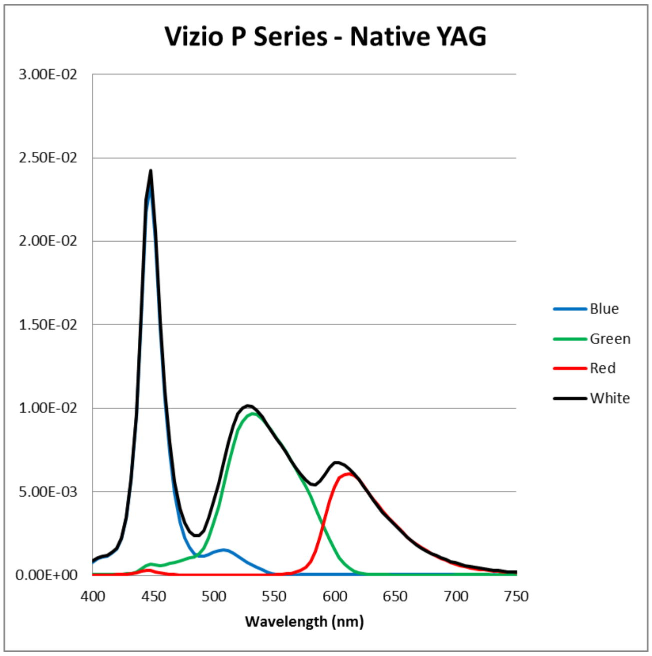
In order to do so, we have built 3 identical test platforms using a commercially available Vizio model P65 direct backlit 65" UHD television. This television is commercially sold using a white LED in the back light. Two additional sets were also purchased, and working with the manufacturer AU Optronics, we obtained 2 identical sets of LED modules with blue LEDs instead of the white ones used in the standard production product. The output power of each LED in optical blue watts was the same at the LED die level as the power in blue watts of the white LED die. Using one set of blue LED modules, we rebuilt the backlight using a state-of-the-art InP (Cd-free) quantum dot conversion sheet (QDEF) which was taken from a Samsung JS8600 65" UHD television. Using the second set of blue LED modules, we rebuilt the backlight using a state-of-the-art CdSe QDEF sheet from 3M. The input power to the television, the color performance, spectrum and white brightness were all measured using a calibrated SpectraScan PR-655 Spectraradiometer. The three sets were shown live at a demonstration by Nanosys at the SID Display Week 2015 conference in San Jose, and Nanosys was award the "Best in Show" award for this exhibition by the SID awards committee[2]. The data and results from this comparison are shown below.

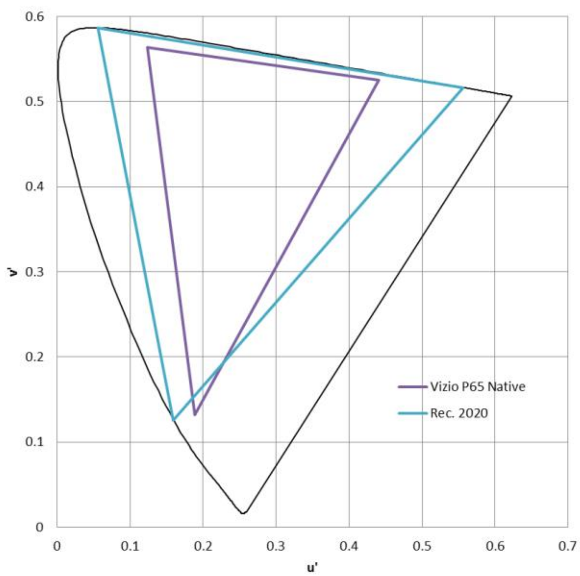
[1] RSJ Consulting, What are RoHS Exemptions, http://www.rsjtechnical.com/WhatareRoHSexemptions.htm
[2] http://www.sid.org/About/Awards/BestinShowAwards.aspx

## Results

### Native P65 with YAG Phosphor LED

The “out of the box” performance of the Vizio P65 set using the highest power backlight setting was measured as 450nits at the front of screen when viewed with a white image. The spectral characteristics were measured as follows.



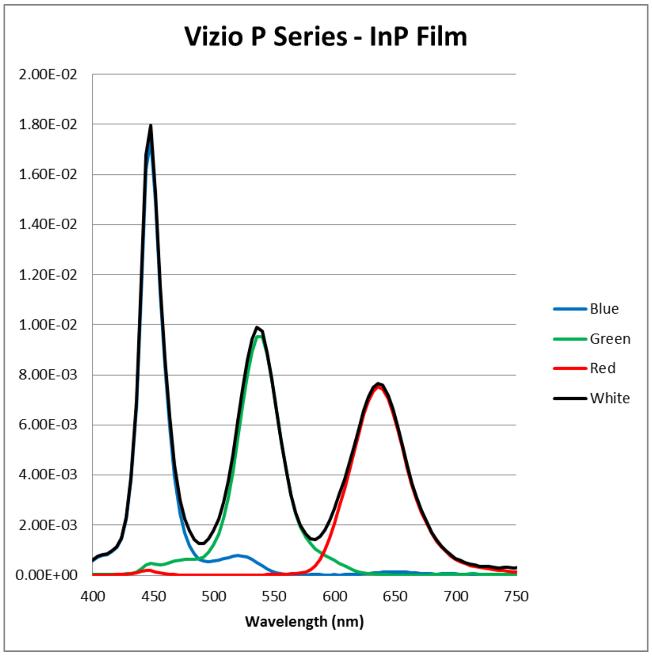



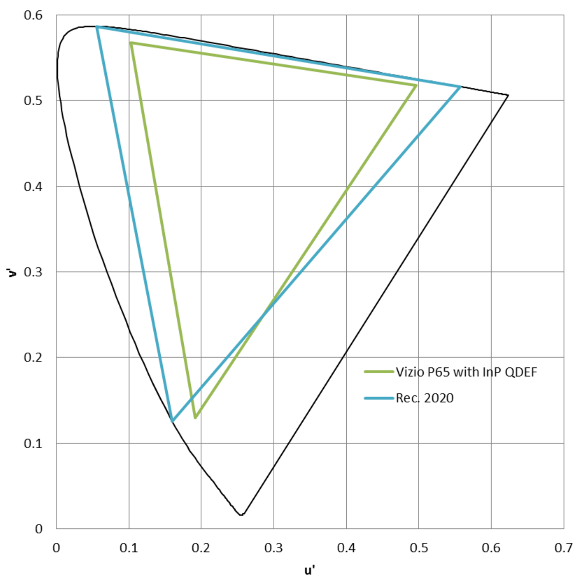

This set has a native white point of 6045K and Rec2020 (BT2020) color gamut coverage of 59.6%. This is an important attribute to measure as the new UHDA content standard specifies data will be transmitted with 100% Rec2020 color performance.[3] As set manufacturers will aspire to achieve at least 90% DCI-P3 color performance, which this set does not at <80% of DCI-P3, and in many cases will seek to hit 90% or more of the Rec2020 color space performance, the impact of higher color gamut cost in terms of efficiency must be a key consideration. Clearly, the Native YAG LED based system used in this set could not meet the higher color gamut requirements and would not qualify as a UHDA color gamut compliant set.

[3] http://www.twice.com/uhd-alliance-defines-premium-4k-ultra-hd-experience/59997

## P65 with Blue LED Back light and Cd-free QDEF

The performance of the Cd-free QD P65 set using the highest power backlight setting was measured as 350nits at the front of screen when viewed with a white image. The spectral characteristics were measured as follows.

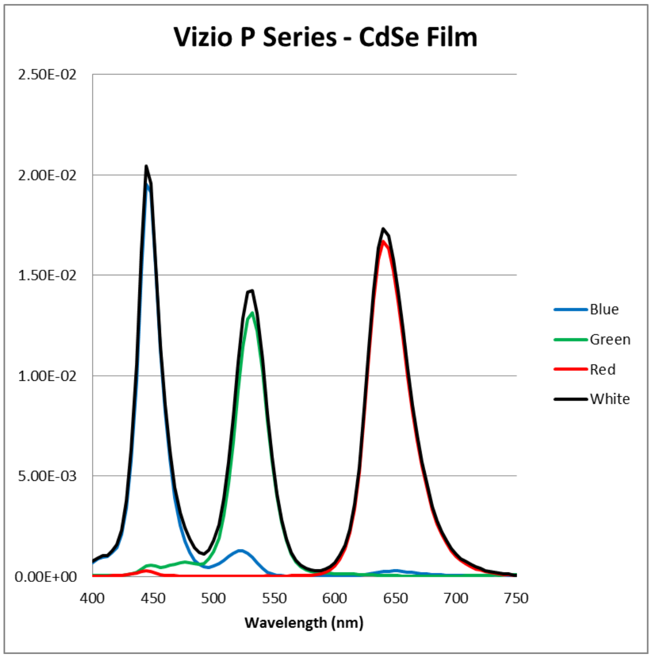


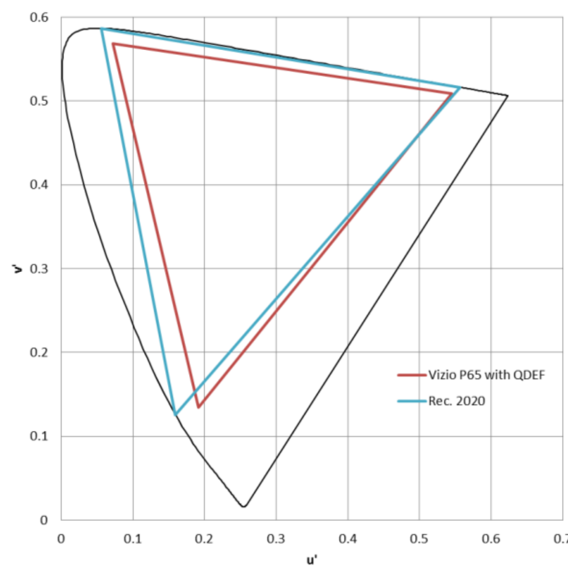




This set has a native white point of 6597K and Rec2020 (BT2020) color gamut coverage of 73.7%. This set does achieve 92.7% of the DCI-P3 specification and would therefore meet the color gamut requirements to be a UHDA compliant set, but overall brightness using the same input power is severely impacted. With only 350 nits out, this set can be seen have 23% less front of screen brightness than the YAG LED based set.

## P65 with Blue LED Back light and CdSe QDEF

The performance of the CdSe QD P65 set using the highest power backlight setting was measured as 400nits at the front of screen when viewed with a white image. The spectral characteristics were measured as follows.




This set has a native white point of 7589K and Rec2020 (BT2020) color gamut coverage of 85.4% and also achieves 94% of the DCI-P3 specification and would therefore meet the color gamut requirements to be a UHDA compliant set. At the same time, the set has output brightness comparable to the YAG set (400 nits vs 450nits.)

## Analysis and Results

Since the brightness performance across the 3 sets is not an entirely accurate reflection of the technology capability due to differences in the spectrum (by design) and the eye response, we can quantify the differences in conversion efficiency more accurately across the 3 systems by using the measured intensity and spectrum data to calculate how many photons each set is producing. Given that the input number of photons is the same in each case, this should more accurately represent the difference in conversion efficiency.

To do so, we start by using Planck's constant to calculate the energy of each photon at each wavelength as $E=hc/\lambda$ and then divide that photon energy level (in Watts) into the measured radiometric intensity (in (W/m^2*sr*nm.) Doing so for each wavelength allows us to calculate the total number of "white" photons that are under each of the spectral curves. These results are shown in the table below.

| | Total white photons (photons/s*m^2*sr) | Ratio to YAG | Ratio to CdSe |
|---|---|---|---|
| YAG | 4.84715E+18 | 1.00 | 0.93 |
| InP | 3.94885E+18 | 0.81 | 0.76 |
| CdSe | 5.22283E+18 | 1.08 | 1.00 |

Given that the input power (optical) to each of the displays is the same, (as is the set power which was measured at 130 watts), we can see that the CdSe QDEF system is the most efficient, converting 7% more of the input photons to output photons than the YAG set. The 10% difference in brightness for the CdSe set is therefore demonstrated to be entirely due to the choice of peak wavelengths which were set to achieve a higher coverage of the Rec2020 color gamut. On the other hand, due to both the lower efficiency of the InP film and the wider FWHM of the Cd-free QDs resulting in more color filter losses, has both 19% lower photon conversion efficiency than the conventional, commercially available YAG LED based set, and 24% lower photon conversion efficiency than the CdSe QDEF set.

## Conclusion

Cd-free (InP) quantum dots have progressed significantly in the past year from being the subject of academic papers and conjecture to being used in successful commercial products. However, they are not the dominant quantum dot technology in use today with only Samsung using them in commercially available products where as others have shown that there are more than 20 SKUs from other manufacturers using CdSe quantum dots. As an available substitution, we have shown here that the Cd-free quantum dots used by Samsung produce 24% fewer photons from the same input power, which as others have shown has a significant LCA impact. While we believe that Cd-free quantum dots will continue to make progress over the coming year, we would recommend based on our analysis and review of the LCA report from 3M that 2013-5 be granted for at least one year.