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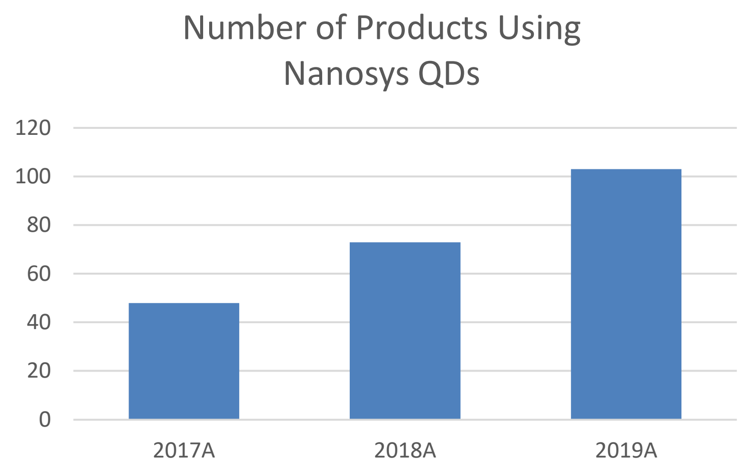
QUANTUM DOTS FOR SOLID STATE LIGHTING

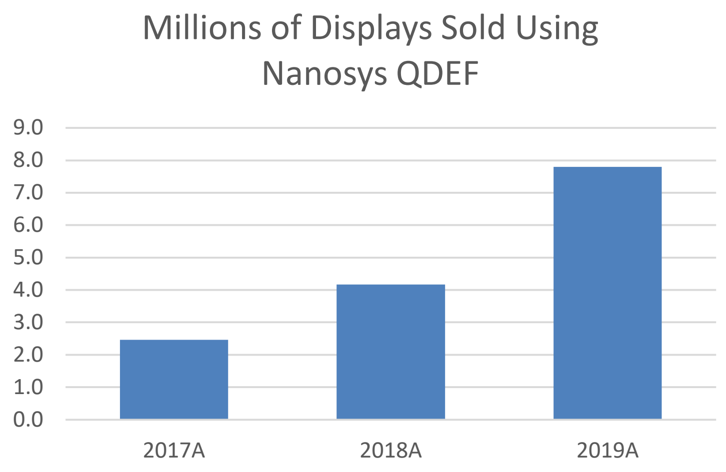
JASON HARTLOVE

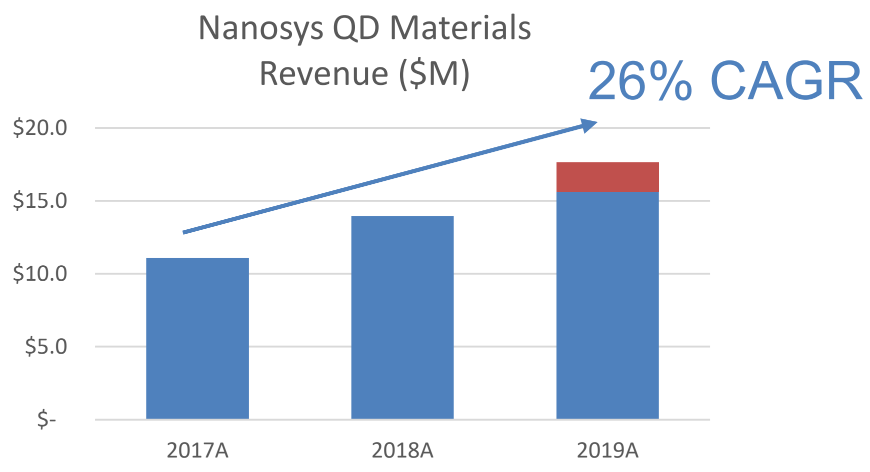
Nanosys Created the Market for QD Display

- Over 250 SKUs shipped using Nanosys technology
- Over 15MU to date in the field
- ~100% of all products shipped in 2019 from Nanosys supply chains
- Over 470 granted and pending patents worldwide

Track Record of Demonstrated Growth and Performance



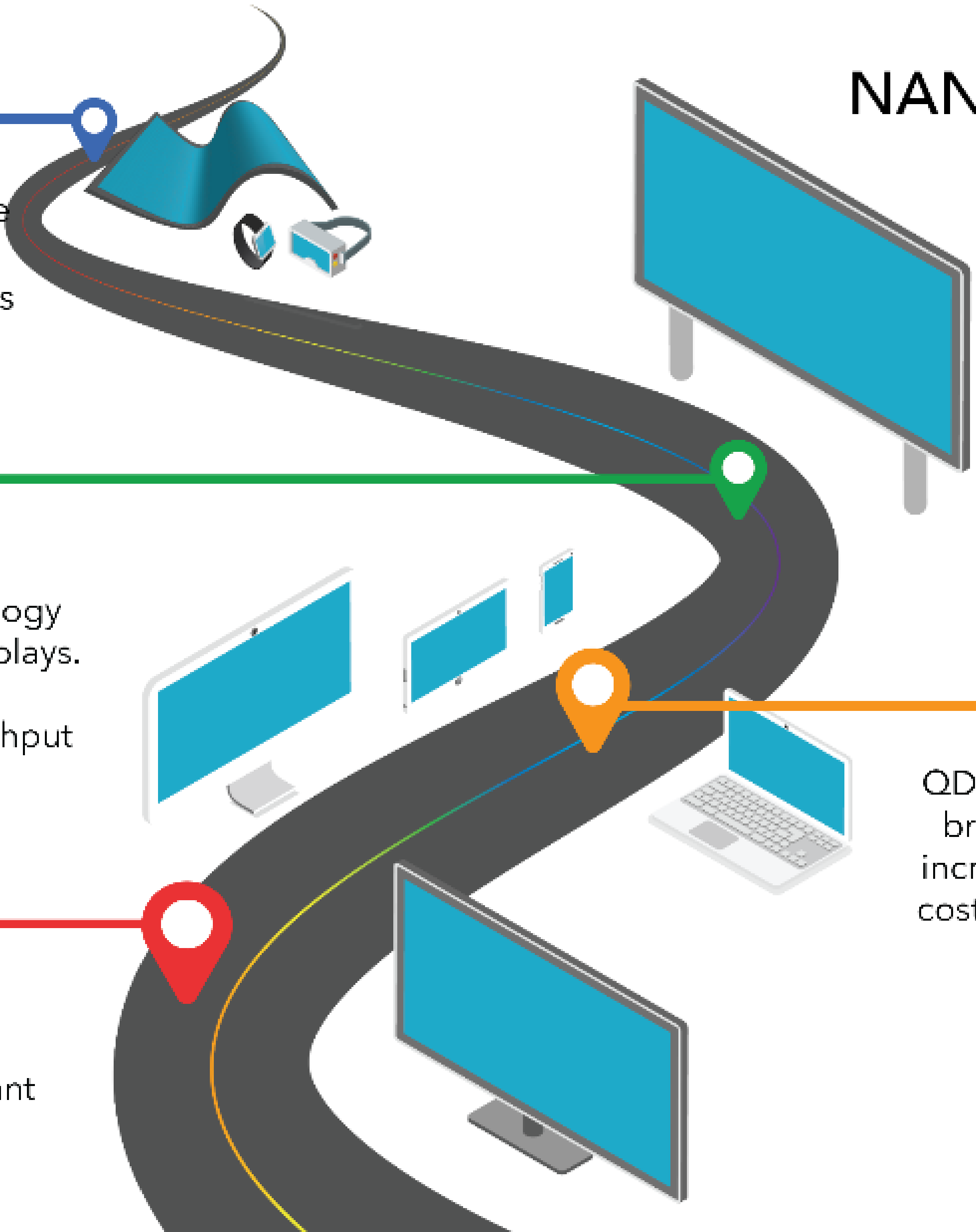




QUANTUM DOT FOR DISPLAY

NANOSYS ROADMAP

Exclusively focused today on display industry



4 QDEL

Quantum Dot Electroluminescent

The future emitter material for emissive displays, QDEL will finally make low-cost, ultra-thin and flexible displays a reality.

3 QDCC

Quantum Dot Color Conversion

Printed or photo lithography-patterned Quantum Dot Color Conversion technology improves LCD, microLED and OLED displays. With QDCC, new levels of color volume performance and manufacturing throughput are possible for all three technologies.

2 QDOG

Quantum Dot on Glass

QDOG Delivers all of the color and brightness benefits of QDEF in an incredibily thin package. This lower cost QD implementation eliminates the need for barrier films and enable 5mm-thin LCD TVs.

1 QDEF

Quantum Dot Enhancement Film

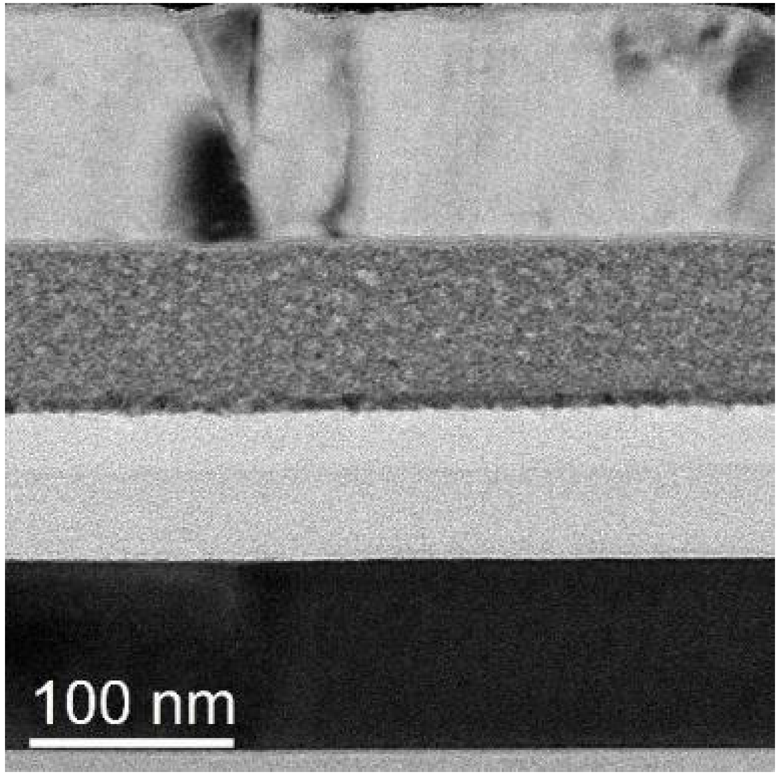
Enabling a new generation of brighter, more efficient diplay with lifelike colors, QDEF gives LCD technology an important edge as it battles new entrants such as WOLED.

QUANTUM DOT FOR SSL

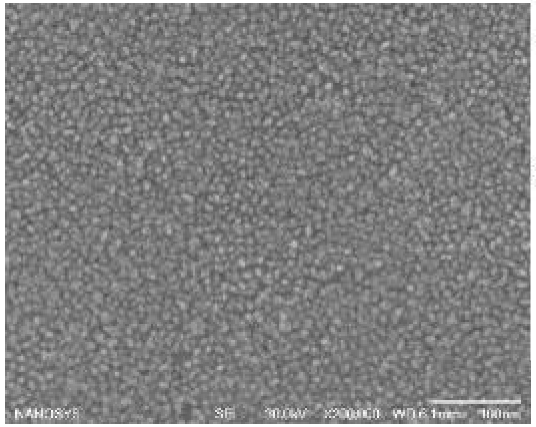
- **QDPL for optical down converters**
  - **Narrower red for high efficiency**
  - **Cyan down converter for color tuning**

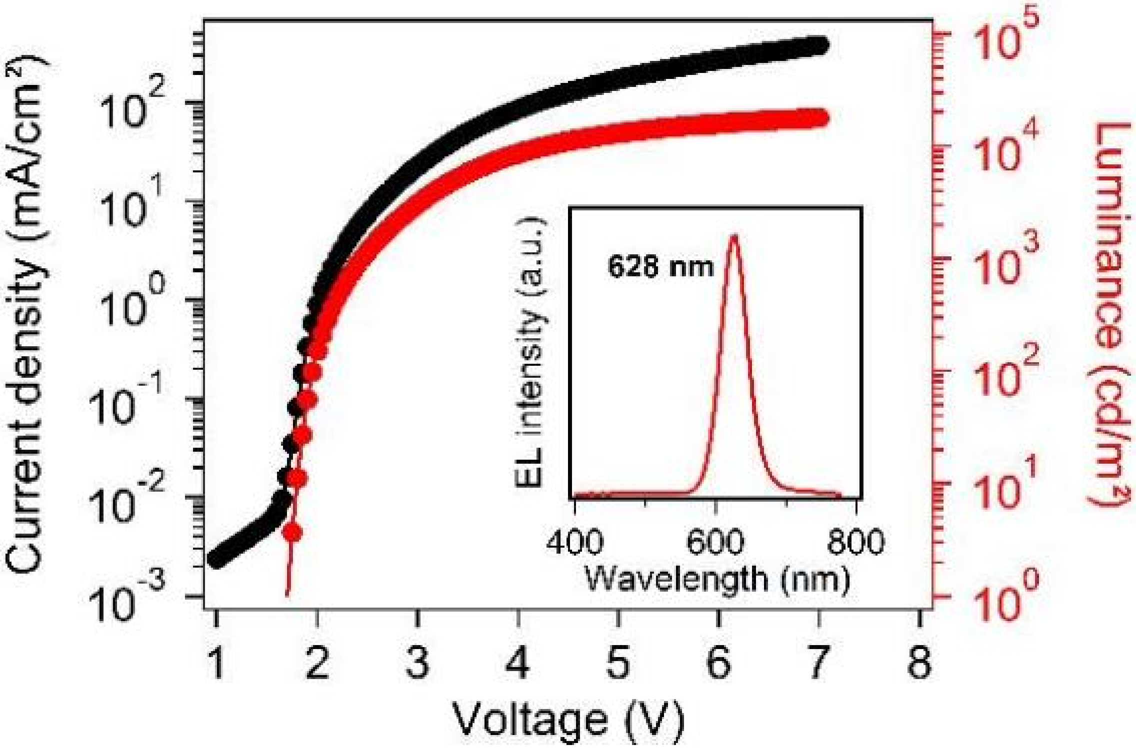
- **QDEL for diffuse light source**
  - **Introduction**
  - **Advantages of QDEL**
  - **Challenges of QDEL and how DOE can help**

QDEL STRUCTURE



Cross section





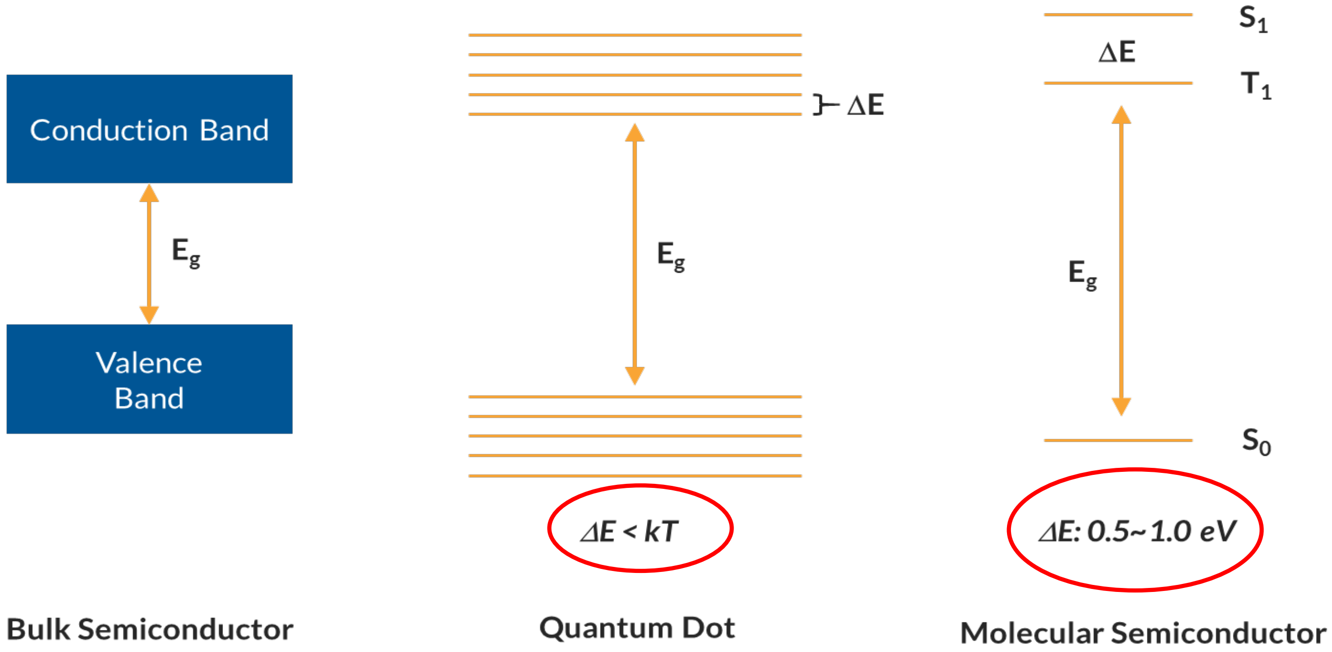
Plane view

Nanosys, DW2019

- **All layers except Al are solution processed**

QDEL ADVANTAGE: EFFICIENCY¥EQE

$$\eta_{EQE} = \eta_{IQE}\eta_{OC}$$



η_{EQE}: External quantum efficiency (%)

η_{IQE}: Internal quantum efficiency (%)

η_{OC}: Light extraction efficiency (%)

$$\eta_{EQE} = \eta_{IQE}\eta_{OC}$$

- **Efficiency as high as phosphorescent OLED system**
  - **Up to 100% IQE**
  - **More OC techniques due to solution process**

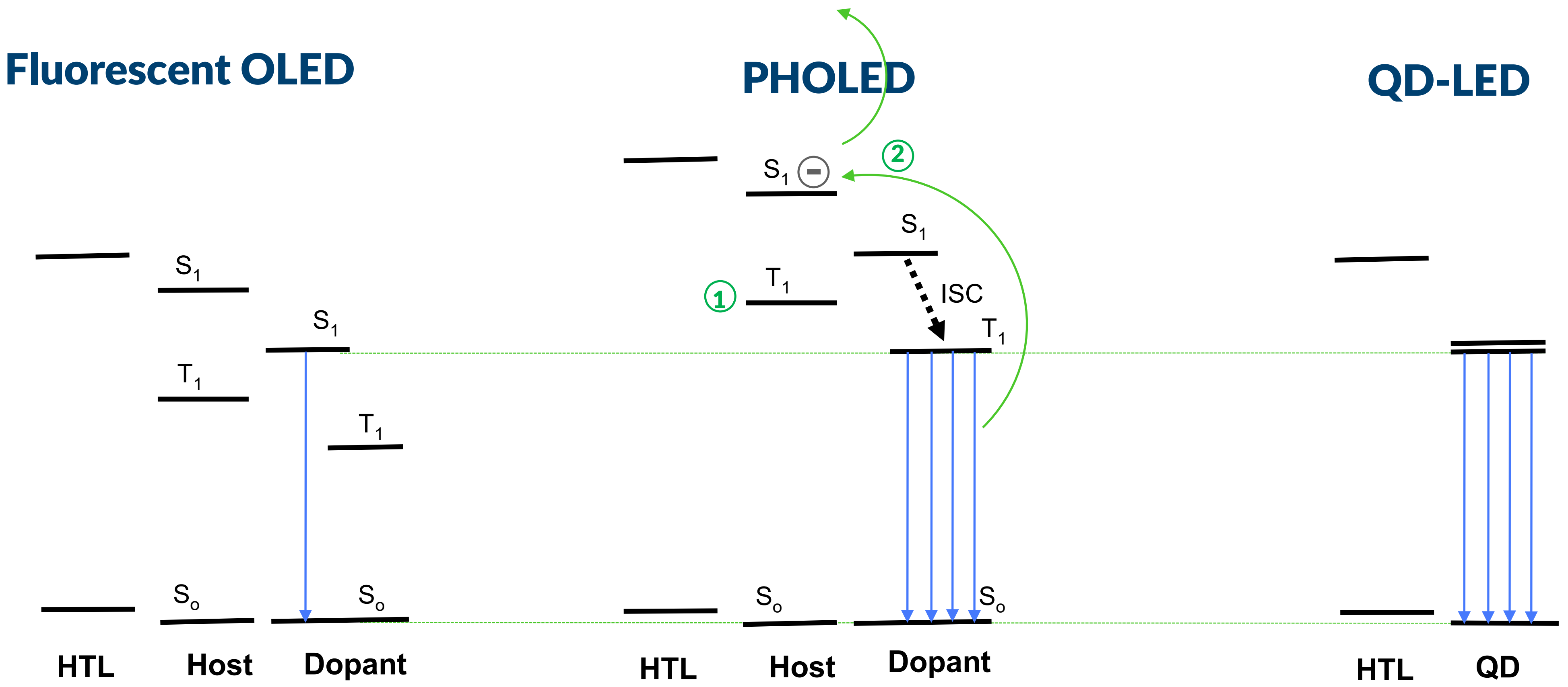
QDEL ADVANTAGE: EFFICIENCY¥LOW VOLTAGE

$$\textit{Power Efficiency} \sim \frac{\eta_{EQE}}{V}$$

V @500nits	PHOLED	QDEL
Red	2.9*	2.1
Green	3.9**	2.5
Blue	5.5***	3.7

* DOI: 10.1021/acsami.6b14438
** DOI: 10.1126/sciadv.aar8332
*** DOI: 10.1021/cm3010453

QDEL ADVANTAGE: LIFETIME



[2] N. C. Giebink, Direct evidence for degradation of polaron excited states in organic light emitting diodes Journal of Applied Physics (2009)

- **Lifetime not dependent on high triplet energy host**

QDEL ADVANTAGE: SPECTRUM ENGINEERING

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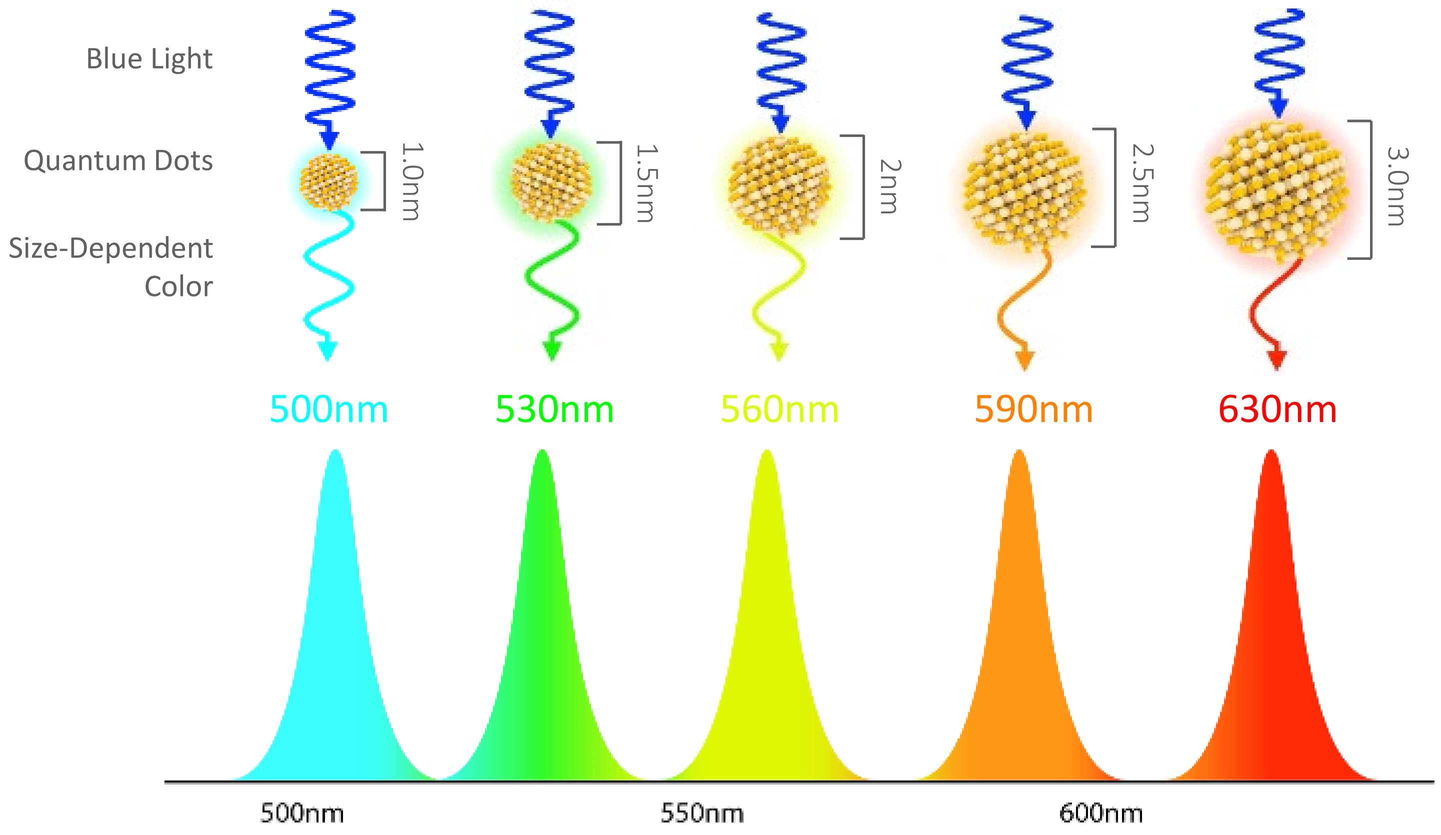
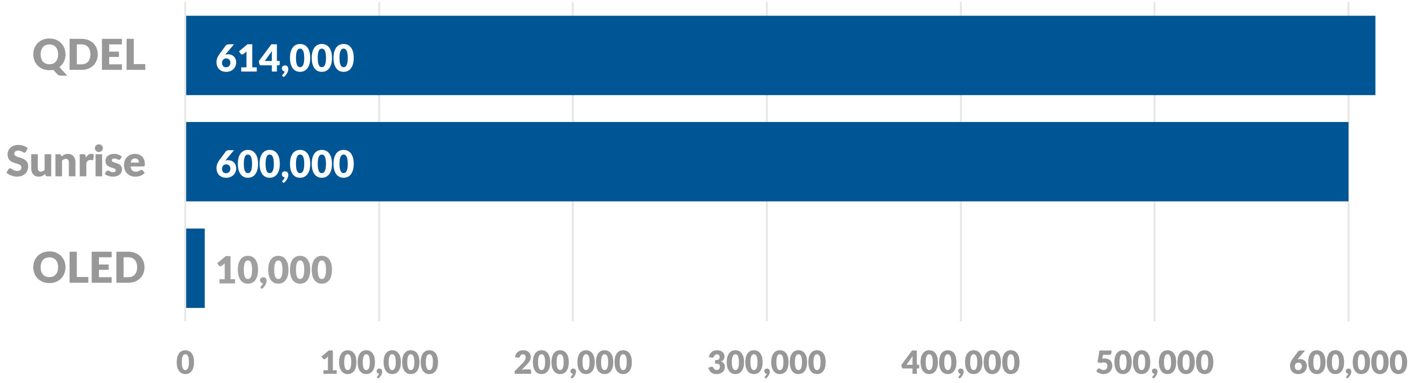


Precisely producing the desired spectrum also leads to higher power efficiency (no “waste”)

QDEL ADVANTAGE: BRIGHT



Source: *"Visible quantum dot light-emitting diodes with simultaneous high brightness and efficiency"* **Nature Photonics volume 13, pages192–197 (2019)**

CASE STUDY: AUTOMOTIVE LIGHT

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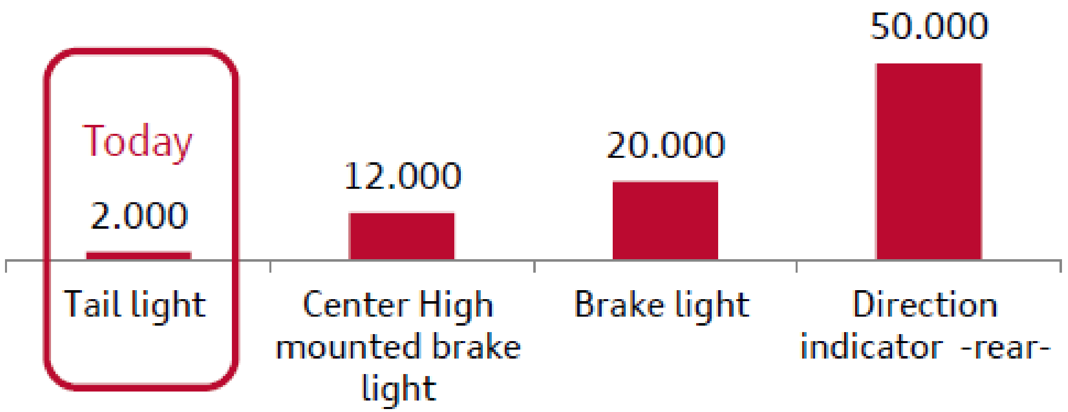
- **Brightness [cd/m²]:**



Source: *Audi presentation, OLED Summit* (2019)

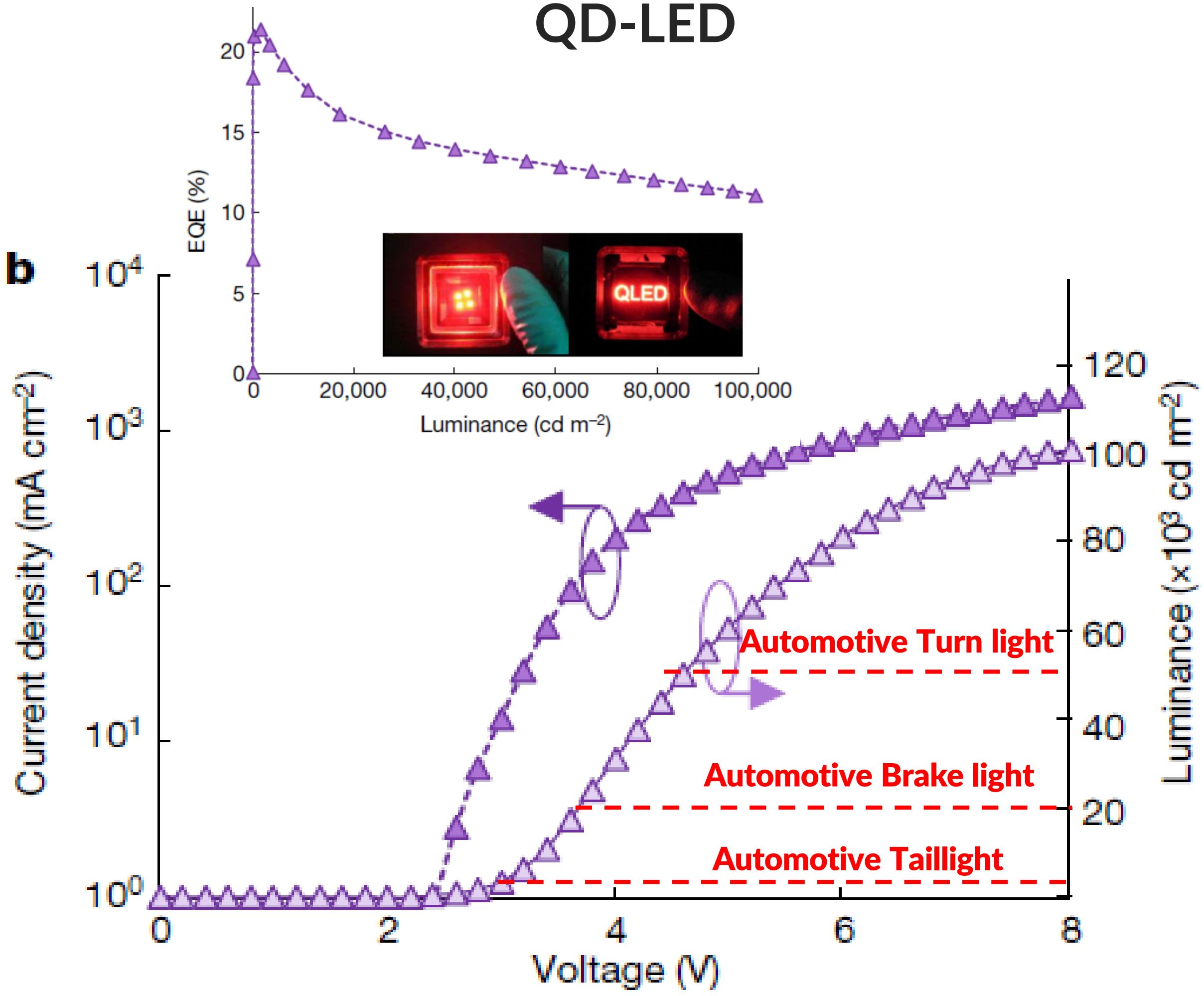
OLED

	Anode	Voltage (V)	cd/m^2	lm/W	cd/A
S2S device	IZO	10.4	900	7.8	26
1st R2R device	IZO/Metal/IZO	18	700	3.2	20
2nd R2R device	IZO/Metal/IZO	12.8	750	4.2	19

Module size: 20cm x 5cm
Device: 3 Tandem deep red
Substrate: plastic

Source: *ITRI presentation, OLED Summit* (2019)

QD-LED



Source: *"Highly efficient and stable InP/ZnSe/ZnS quantum dot light-emitting diodes"*
Nature volume 575, pages634 (2019)

QDEL ADVANTAGE: LOW COST

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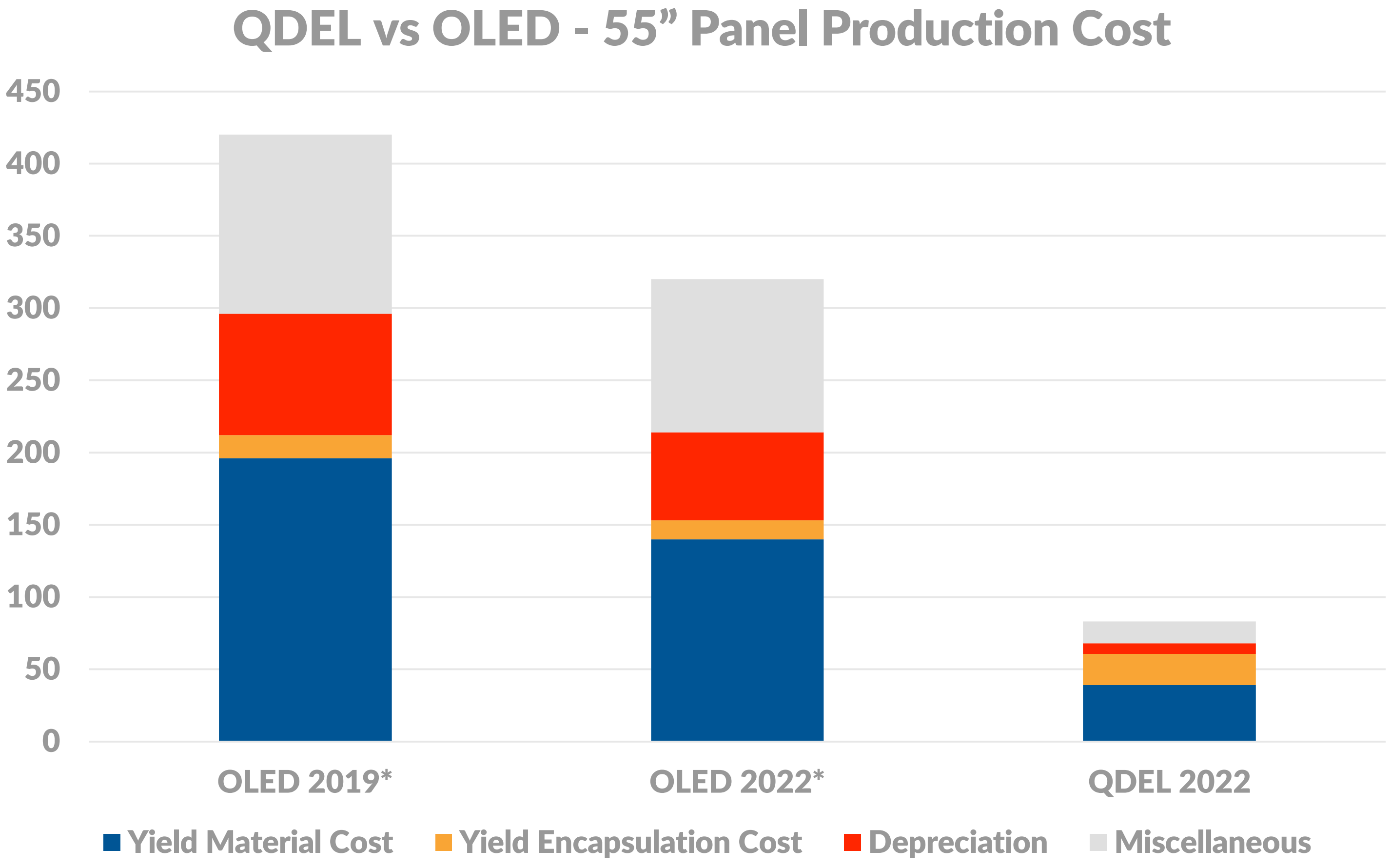
Inkjet Printed QDEL Display

Source: Nikkei Tech

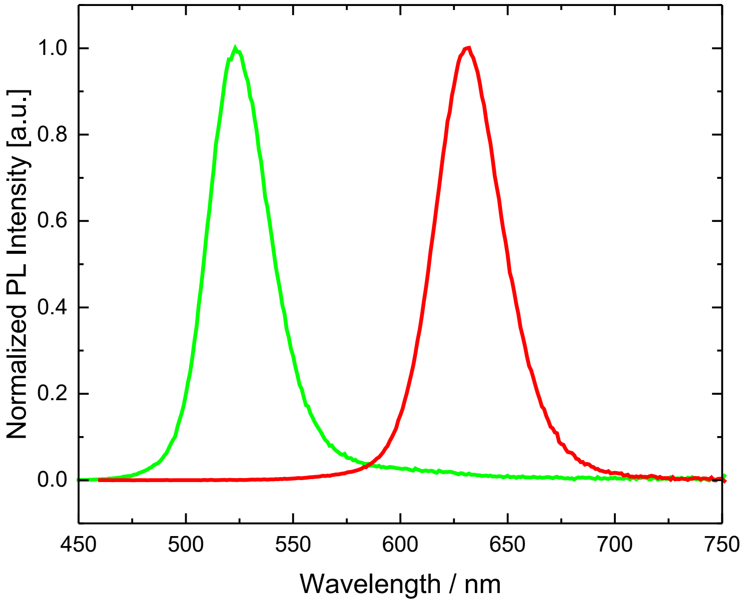
Future Gravure Printed QDEL

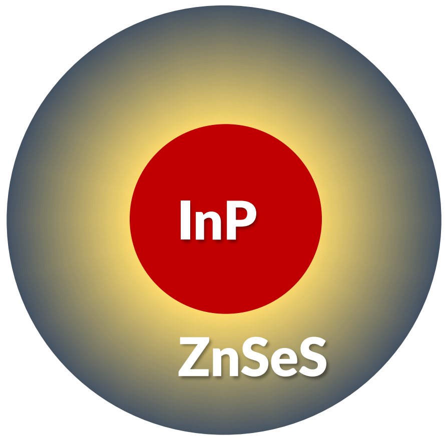


*Source: DSCC, QD Forum 2019

- **Highly efficient InP QDs with narrow spectra for red and green**

Material	Color	PWL (tunable)	FWHM	QY
InP	Green	520-540 nm	34 nm	>95%
InP	Red	620-640 nm	37 nm	>95%

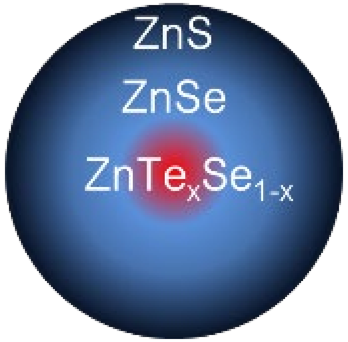


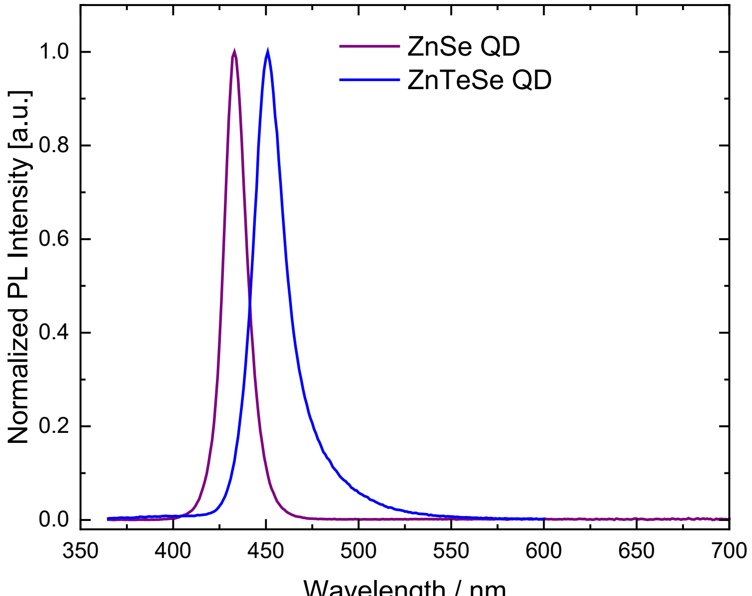


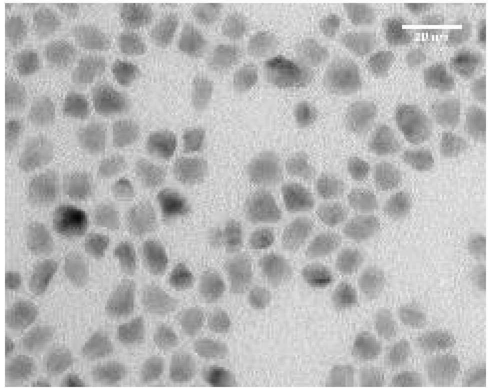
BLUEQDS

- **PWL tunable in 430 to 470 nm range**
- **High QY, narrow FWHM**

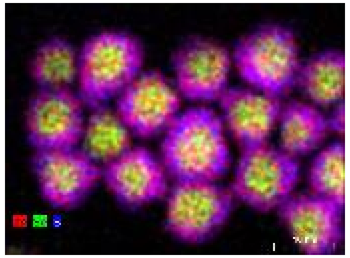
Material	Color	PWL	FWHM	QY
ZnSe	Violet	433 nm	15 nm	90%
ZnTeSe	Blue	451 nm	21 nm	90%







Crystalline particles
Conformal shells



QDEL EQE MILESTONES

Color	EQE
Red	16.9%
Green	17.6%
Blue	12.5%

QDEL LIFETIME MILESTONES

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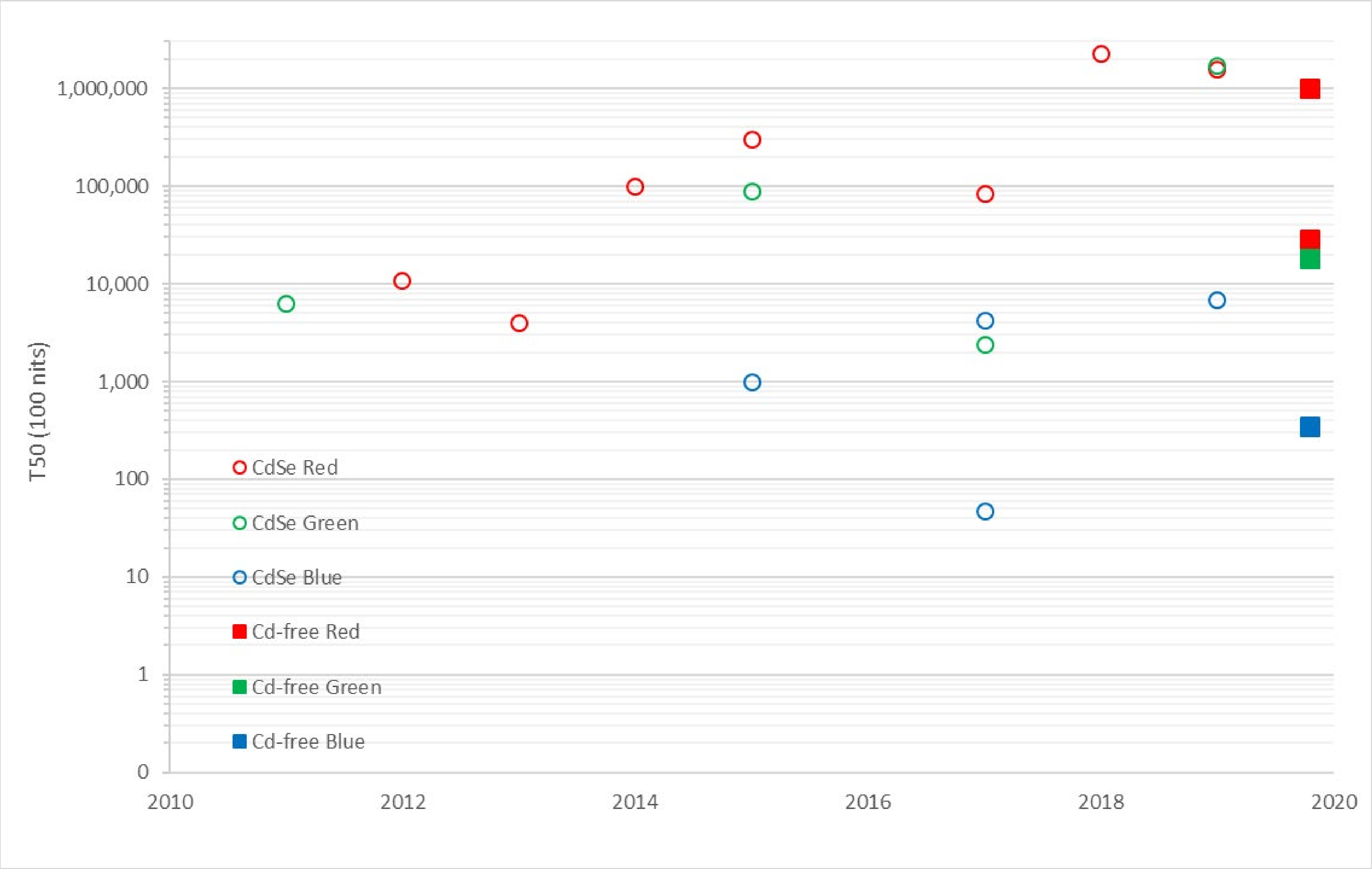

SUMMARY

- **QDEL has great potential as diffuse light source**
  - **High power efficiency – up to 100% IQE; low voltage; more ways for light extraction**
  - **Spectrum engineering for color management and high efficiency**
  - **Super bright at low voltage**
  - **Low cost solution process and easy color patterning**
  - **Compatible with many aspects of OLED lighting: substrate, light extraction, encapsulation, driving…**
- **QDEL challenge**
  - **Only significant challenge is to improve lifetime for commercial applications (EQE is already good, can be easily improved further)**
  - **DOE funding would make a huge impact at this stage of development**

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