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Nanomanufacturing - Product specification - Part 4-3: Nanophotonic products - Blank detail specification: quantum dot enabled light emitting diodes

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Nanomanufacturing - Product specification - Part 4-3: Nanophotonic products - Blank detail specification: quantum dot enabled light emitting diodes

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The text of this Technical Specification is based on the following documents:

Draft	Report on voting
113/956/DTS	113/975/RVDTS

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this Technical Specification is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/publications.

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Future standards in this series will carry the new general title as cited above. Titles of existing standards in this series will be updated at the time of the next edition.

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INTRODUCTION

This document details how to specify the key control characteristics of quantum dot enabled light emitting diodes (QLEDs) in a systematic and consistent manner. It gives the key control characteristics (KCCs) and corresponding measurement methods related to QD materials, QD inks, QD films and QLED prototype devices.

Typically, the applications of QDs in displays have two technological pathways: photoluminescence (PL) and electroluminescence (EL). The former is passive luminescence, where green and red light is generated by excitation via higher energy blue light illumination. The latter is active luminescence. In electroluminescent QLEDs, electrons and holes are injected into the colloidal QD emissive layer to form excitons that then radiatively decay to release photons. Electroluminescent QD display technology has become more and more appealing in research and industry recently due to its high contrast, fast response, foldability, and ultra-thin structure, as compared with the use of photoluminescent QDs.

The importance of QDs to QLED performance cannot be overemphasized. Specifically, its chemical composition, core-shell structure, crystallinity, energy levels for both conduction and valence bands, static optical properties, ultrafast optical properties and so on have been demonstrated repeatedly in numerous publications to play major roles in affecting device internal quantum efficiency (IQE), external quantum efficiency (EQE) and stability. Slight QD material modifications lead to noticeable changes in the device performance. Although multiple characterizations for each of these factors have been reported in different publications, thus far there are no unanimous protocols established. Therefore, it is important to report a systematic and well-accepted protocol of characteristics.

Preparation of QD inks suitable for the ink-jet printing techniques is crucial for the mass production of QLED-based displays. This is a non-trivial assignment since the quality of ink-jet printed films is closely related to the properties of the inks. On one hand, it is important to preserve the solubility and optical stability of QDs; and on the other hand, the inks' compatibility with substrate and process conditions is crucial to produce excellent films. Decent progress has been made, but there is still more to be done to achieve reproducible high-quality films. Standardization of the detailed physical properties will definitely facilitate this process.

Film qualities for QDs as well as other functional layers – including electron transfer, hole transfer, and hole injection layers – are directly related to the balance of carrier injections, which is highly correlated to the device performance. Thus, it is extremely important to develop the ability to reproducibly prepare uniform film. Characterizations of film thickness, uniformity, QD optical stability, physical stability and conductivity are necessary to assure the quality of prepared films.

The luminance of QLEDs is one of the most important parameters, determining the accuracy of device lifetime conversion. Unfortunately, despite its significance, the reported results from different laboratories and institutes contradict each other. Currently, there are three widely used methods for this measurement. They are spectroradiometer, silicon photodetector and integrating sphere. It turns out the major discrepancies arise from the different methods used. Particularly for prototype QLEDs, different luminance measurement methods lead to rather different results. Therefore, the standardization of luminance measurement for QLEDs is urgent in order to obtain reliable results. And this is the cornerstone for the further improvement of QLED research.

This document also provides information about measurement methods and existing standards concerning the correct determination of key control characteristics.

1 Scope

This part of IEC 62565 establishes a blank detail specification (BDS) for quantum dot enabled light emitting diodes (QLEDs) used for printed light emitting diodes (LEDs).

This document is intended to be used for display applications.

The relevant key control characteristics (KCCs) include optical, physical, chemical, and structural properties of colloidal quantum dots (QDs). For each KCC listed, methods and existing standards for their measurement are reported. The applicability of such methods and standards to different material categories (physical forms) of QDs, for example colloidal solution, inks, films, is indicated.

Numeric values for the KCCs are left blank as they will be specified between customer and supplier in the detail specification (DS). In the DS, KCCs can be added or removed if agreed between customer and supplier.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 61010-2-033:2023, *Safety requirements for electrical equipment for measurement, control, and laboratory use - Part 2-033: Particular requirements for hand-held multimeters and other meters for domestic and professional use, capable of measuring mains voltage*

IEC TS 62565-4-2:2018, *Nanomanufacturing - Material specifications - Part 4-2: Luminescent nanomaterials - Detail specification for general lighting and display applications*

IEC 62595-2-1:2016, *Display lighting unit - Part 2-1: Electro-optical measuring methods of LED backlight unit*

IEC 62607-3-1:2014, *Nanomanufacturing - Key control characteristics - Part 3-1: Luminescent nanomaterials - Quantum efficiency*

IEC TS 62607-3-3:2020, *Nanomanufacturing - Key control characteristics - Part 3-3: Luminescent nanomaterials - Determination of fluorescence lifetime of semiconductor quantum dots using time correlated single photon counting (TCSPC)*

IEC TS 62607-5-1:2014, *Nanomanufacturing - Key control characteristics - Part 5-1: Thin-film organic/nano electronic devices - Carrier transport measurements*

IEC TS 62607-6-8:2023, *Nanomanufacturing - Key control characteristics - Part 6-8: Graphene - Sheet resistance: In-line four-point probe*

IEC TS 62607-6-20:2022, *Nanomanufacturing - Key control characteristics - Part 6-20: Graphene-based material - Metallic impurity content: Inductively coupled plasma mass spectroscopy*

IEC 62899-203:2024, *Printed electronics - Part 203: Materials - Semiconductor ink*

IEC TR 63258:2021, *Nanotechnologies - A guideline for ellipsometry application to evaluate the thickness of nanoscale films*

ISO 15989:2004, *Plastics - Film and sheeting - Measurement of water-contact angle of corona-treated films*

OECD 114:2012, *Viscosity of Liquids*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

- IEC Electropedia: available at https://www.electropedia.org/
- ISO Online browsing platform: available at https://www.iso.org/obp

3.1 General terms

3.1.1
conduction band edge
minimum energy of the allowed energy band partially occupied by quasi-free electrons

Note 1 to entry: The electrons on conduction band are mobile and responsible for electric conductivity of QD film.

Note 2 to entry: Matching the conduction band of the electron transfer layer with that of QD film facilitates electron transfer.

[SOURCE: IEC 60050-113:2011, 113-06-20, modified – In the term, "edge" has been added. In the definition, "minimum energy of the" has been added. Notes 1 and 2 to entry have been added.]

3.1.2
valence band edge
maximum energy of the allowed energy band completely occupied by electrons at a thermodynamic temperature of zero kelvin

Note 1 to entry: Holes on valence band are mobile and responsible for hole conductivity of QD film.

Note 2 to entry: Matching the valence band of the hole transfer layer with that of QD film facilitates hole transfer.

[SOURCE: IEC 60050-113:2011, 113-06-19, modified – In the term, "edge" has been added. In the definition, "maximum energy of the" has been added, "band" has been replaced with "energy band", "completely" has been added, and "the valence electrons" has been replaced with "electrons". Notes 1 and 2 to entry have been added.]

3.1.3
single exciton lifetime
time it takes for an exciton to decay to the ground state

Note 1 to entry: Quantum lifetime is within the range of tens of nanoseconds.

Note 2 to entry: An exciton is a pair of electron and hole confined in QDs created by photo excitation or carrier injection.

3.1.4
Auger recombination

non-radiative process where the excess energy from the electron-hole recombination is transferred to electrons or holes that are subsequently excited to higher energy states within the same band instead of giving off photons

Note 1 to entry: Due to discrete energy states near the band edge of QDs, Auger recombination rate is much slower than that of bulk material.

Note 2 to entry: Auger recombination of a negative trion, for instance, can be described in terms of Coulomb scattering between the two electrons in the conduction band and one hole in the valence band when one pair of electron and hole undergoes recombination while the remaining electron is excited within the conduction band. Auger recombination of a neutral biexciton can involve re-excitation of either an electron (negative trion pathway) or a hole (positive trion pathway).

3.1.5
viscosity

property of a liquid resulting from internal flow resistance opposing the relative movement of adjacent layers

[SOURCE: IEC 60050-212:2010, 212-18-03, modified – In the term, "(dynamic)" has been deleted. The note has been deleted.]

3.1.6
wettability

ability of a solid material to absorb a liquid

Note 1 to entry: A measure of wettability is the contact angle between the solid surface and the liquid surface of a drop of the liquid on the solid.

Note 2 to entry: The liquid for which the wettability is determined is not necessarily water.

[SOURCE: IEC 60050-212:2010, 212-12-21, modified – In the definition, "surface" has been deleted and "adsorb" has been replaced with "absorb".]

3.1.7
surface tension

γ

at a point of a line on the interface of two fluids or a fluid and a solid, quantity equal to the derivative of component F of the force, tangent to the surface and perpendicular to the line, with respect to curvilinear abscissa l

$$\gamma = \mathrm{d}F/\mathrm{d}l$$

Note 1 to entry: The surface tension is equal to the work ΔW needed to expand the surface by an area ΔA, divided by ΔA, thus $\gamma = \Delta W / \Delta A$.

Note 2 to entry: The coherent SI unit of surface tension is newton per metre (N/m) or, equally, joule per square metre ($\mathrm{J/m^2}$).

[SOURCE: IEC 60050-113:2011, 113-03-42]

3.1.8
film uniformity

measurement of the degree of variations in the film surface topology, typically characterized by surface roughness

3.1.9

carrier mobility

average drift velocity of carriers per unit electric field in a homogeneous semiconductor

Note 1 to entry: The carrier mobility of electrons is usually different from that of holes.

Note 2 to entry: Determining the carrier mobility from a simple measurement of resistivity and carrier concentration gives a measure of the transport mean free time (or lifetime), τ, through the relation $\mu = e\tau/m$, where e is the magnitude of the electric charge carried by a single electron, and m is the effective mass of the charge carrier.

Note 3 to entry: Carrier mobility is typically defined as $\mu \equiv v/E = \sigma/en$, where v is the Drude carrier drift velocity, E is applied electric field, assumed to be small, σ is conductivity, e is the magnitude of the electric charge carried by a single electron, and n is carrier density.

Note 4 to entry: Carrier concentrations and carrier mobilities for a sample can be determined from measurements of the Hall coefficient and resistivity as a function of temperature.

[SOURCE: McGraw-Hill Dictionary of Scientific and Technical Terms, sixth edition, modified – The second part of the source definition has been moved to Note 1 to entry. Other notes to entry have been added.]

3.1.10

sheet resistance

electric resistance of a thin film material measured across the opposite ends of a square area

Note 1 to entry: The unit of sheet resistance is expressed in ohms (Ω). However, for the purpose of this procedure, it represents the unit of ohms per square (Ω/sq) with the thickness of the film.

[SOURCE: IEC 62899-202-3:2019, 3.1]

3.1.11

integrating sphere

hollow sphere, the interior of which is formed from, or coated with, a diffusely reflecting material that is as spectrally neutral and as spatially uniform as possible

Note 1 to entry: Owing to the internal reflections within the sphere, the illuminance on any part of the inside surface of the sphere for which the direct flux is hidden is theoretically proportional to the luminous flux entering the sphere or produced inside the sphere. The illuminance of the internal sphere wall can be measured via a small window.

Note 2 to entry: The window of an integrating sphere is often used in radiometric measurement systems to provide a source with good spatial uniformity and with an angular distribution of radiance or luminance that is close to Lambert's cosine law.

[SOURCE: IEC 60050-845:2020, 845-25-028]

3.2 Key control characteristics measured in accordance with this document

3.2.1

quantum dot enabled light emitting diode

QLED

light emitting diode in which light is emitted from quantum dots via electroluminescence, as a result of charge carrier injection and radiative recombination within the quantum dots

Note 1 to entry: A QLED comprises basic functional layers including cathode, anode, hole injection layer, hole transfer layer, emission layer, electron transfer layer, etc.

3.2.2

photoluminescence quantum efficiency

quotient of the photon flux of the radiation emitted by a photoluminescent material and the photon flux of the exciting radiation absorbed by that material

Note 1 to entry: The photoluminescence quantum efficiency has unit one.