Nanoparticles for High-Luminance Light-Emitting Diodes for Efficient Automotive Systems

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ABSTRACT

The automotive industry is undergoing some technological revolutions that are shaping the greatest ever upheaval in transportation. These forces are giving rise to three disruptive technological trends: electrification, autonomous vehicles, and digital mobility. In the frame of these revolutions, quantum dots (QDs) might challenge the current lighting emitting diode (LED).

1 Introduction

In the automotive sector, some technological revolutions i.e. electrification, autonomous vehicles, and digital mobility, are taking over fast-paced [1]. Therefore, the vehicles of the future will be much more environmentally friendly thanks to electrification, vehicles will be connected and the driver will delegate more tasks to the car to handle complex traffic situations due to the autonomous revolution and new forms of mobility will arise, where the vehicle will communicate with the road environment [1-4]. Thus, as reported by Aschenbroich [3], "the revolutions currently taking place in the automotive industry are going to disrupt usage patterns so dramatically that it is difficult to know exactly how people will be using cars tomorrow by blurring the distinction between individual and collective transportation".

At the core of those revolutions, automotive lighting systems play an essential and transversal role. Thus, light emitting devices (LEDs) are replacing the use of halogen lamps [5,6]. Those solid-state devices offer a low energy consumption and a long lifetime, which is key in the eventual integration in the electric vehicle, contributing therefore to the carbon footprint reduction.

Moreover, as indicated by Kruppa et al. [7,8], customization and car-to-X communication is a desirable feature in lighting systems since digital information can be shared with the vehicle surroundings, which is vital for the final autonomous vehicle implementation and the desired digital mobility introduced above.

1.1 Visibility Systems

Designing and producing innovative and efficient lighting systems for safer, more comfortable manual driving and for improved and enhanced visibility in autonomous vehicles is required for automotive original equipment manufacturer (OEM) companies like VALEO.

Likewise, its lighting activity is divided in four main domains: front domain, focused on headlamps and illuminated grilles and logos; rear domain, centered on rearlamps; near field projection for static and dynamic welcome light; and interior lighting for the driver and passenger cabin.

1.2 Targets in Automotive Lighting Systems

1.2.1 SAFER

Visibility is the pillar of a safe mobility with the development of high-definition (HD) lighting and communication signaling and projection on the road as shown in the example of Fig. 1, where the car is projecting on the road the turn indicator signal.

Fig. 1 360° Near Field Projection. Designed by Valeo.

1.2.2 APPEALING

Bearing in mind the style, visibility solutions are the soul of car design. Therefore, different developments based on thinner and lighter lighting modules to perform welcome projections are key in the automotive lighting applications as shown in Fig. 2.

Fig. 2 Ultrathin lighting modules and illuminated grilles. Designed by Valeo.

1.2.3 SMARTER

Visibility solutions bring a dynamic digital experience through the HD lighting systems for road marking and interior lighting home-like feeling. This is shown in Fig. 3.

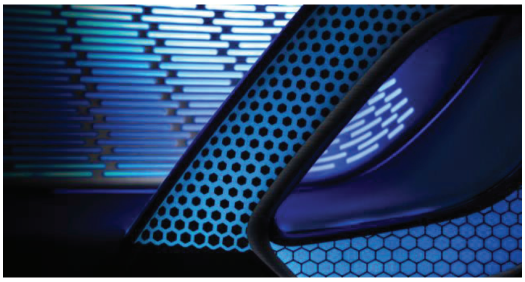

Fig. 3 Backlit systems based on plastic-based surfaces decoration. Designed by Valeo.

1.2.4 GREENER

CO_2 reduction is mandatory to decrease the carbon footprint. Thus, new visibility solutions also bring a lower consumption & weight saving by increasing the efficiency of the new optoelectronic devices used in the lighting modules.

1.3 Automotive lighting sources integration

In order to develop a safe, attractive, smart and green lighting module, the selection of the optoelectronics devices becomes vital. The evolution of the latter is based on the final lighting product desired in the final automotive implementation. As introduced above, the trend clearly goes through multi-segmented lighting surfaces [7,8], where a high level of optical performance, mechanical integration and electronics development is necessary.

Nevertheless, current LED technology, composed of discrete point light source devices, makes this task very complex and costly, since optical-mechanical systems that are difficult to design are required. In addition, numerous LEDs or light-emitting diodes must be used to increase the optical performance, which implies a complex electronics development as shown in Fig.4 as example.

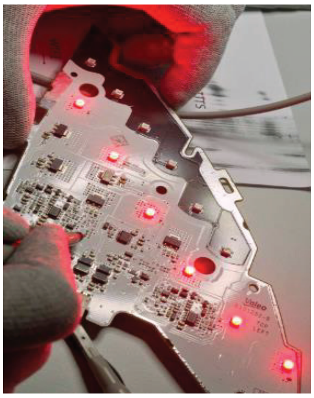

Fig. 4 Optics, mechanics and electronics integration. Designed by Valeo.

Indeed, different approaches are based on the use of optical diffusers to scatter the light in combination with single-color emitting LEDs (for example red LEDs for TAIL or STOP lighting functions; amber or yellow for TURN INDICATOR). However, a dramatic system-based optical efficacy loss happens by using those optical diffusers. In this manner, in order to improve the homogeneity, it is necessary to increase the diffuser material thickness [7-9], which leads to a low-efficiency optical systems as a whole.

Furthermore, a real and automotive validated alternative to cover these technological requirements described above is based on the use of organic LEDs (OLEDs) [6]. However, although the current automotive OLED complies with the car manufacturer requirements, the intrinsic instability of those optoelectronic devices under automotive environment, due to the organic nature, might lead to reduce drastically the lifetime of OLEDs [9-12]. Hence, the possibility to find new potential lighting alternatives for the automotive industry to support and complement the use of the already validated OLED technology could be interesting in the next future of automotive lighting source integration [9].

1.4 Nanotechnology for optoelectronic devices

Nanoparticles known as quantum dots (QDs) could support new automotive lighting sources integration in an effective way. QDs are nanocrystal semiconductors where electrons are confined in a region of space of nanometric dimensions. This implies the existence of a quantum confinement in the three dimensions of space. A particular kind of QDs, the colloidal quantum dots (CQD), are of interest for our purposes [9].

Specifically, LED lighting devices based on quantum dots (quantum dot LEDs), known by their acronym QD-LED or QLED, offer a promising future as a new generation of lighting devices due mainly to three factors [13]:

a) *Purity of color:* Narrow emission bands that can be spectrally positioned by controlling the size of the nanocrystal during its synthesis.
b) *Processability:* Methods of synthesis through colloidal solutions that allow the use of low cost deposition techniques on large surfaces, both rigid and flexible.
c) *Stability:* Composed from inorganic materials, QDs LEDs can be designed to be automotive compliant.

Furthermore, there are two physical mechanisms from which it is possible to take advantage of QDs when it comes to light-emitting devices. First, when an electrical current is used to excite QDs, electroluminescence (EL) phenomena are obtained. Secondly, if that QD excitation comes from a higher energy radiation than the one defined by the QD layer, photoluminescence (PL) phenomenon is considered [9].

2 Experiment and Results

2.1 QLED - Electroluminescence

In this case, the design, manufacturing and numerical simulation approach of a 6-pixel (4.5 mm^2/pixel) electroluminescent quantum dot light emitting device (QLED) based on $CuInS_2/ZnS$ quantum dots as an active layer was implemented [14]. The QLED device was fabricated using a conventional multi-layer thin film deposition. In addition, the electrical I–V curves were measured for each pixel independently, observing how the fabrication process and layer thickness have an influence in the I-V curves. This experimental device shown in Fig.5 enabled us to create a computational model for the QLED based on the Transfer Hamiltonian approach to calculate the current density J (mA cm^{-2}), the band diagram of the system, and the accumulated charge distribution [14].

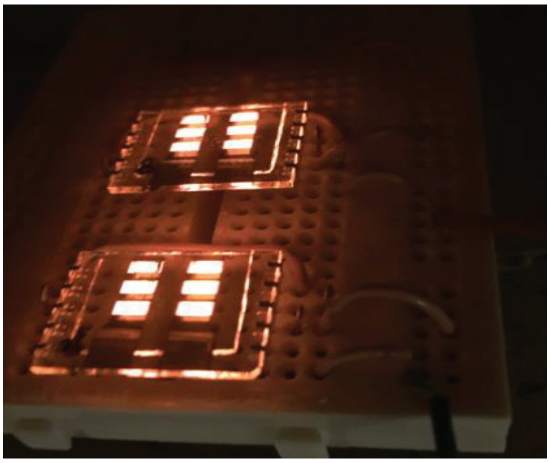

Fig. 5 Image illustrating the QLED fabricated following the structure: Anode / HIL / HTL / EL / ETL/Cathode [14].

Besides, it is worth highlighting that the simulator allows the possibility to study the influence of different parameters of the QLED structure like the junction capacitance between the different multilayer set. Specifically, we found that the Anode-HIL interface capacitance has a greater influence in the I–V curve as shown in Fig.6.

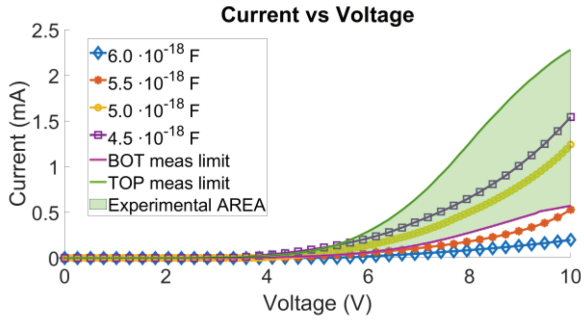

Fig. 6 Figure illustrating the fundamental I-V curve plot. Solid lines indicate the upper and lower measured curves corresponding to the individual pixels from Fig 5. The green area in between shows the variability due to the manufacturing process. Marked curves correspond to the simulation, where the junction capacitance Anode-HIL of the QLED device was gradually varied [15].

That junction capacitance plays an important role in the current density increase and the QLED turn-on value when a forward voltage is applied to the device. Therefore, the simulator could support the selection of the optimal thickness and transport layers during the experimental fabrication process [14,15].

2.2 QD-LED - Photoluminescence

On the other hand, a design of a 60-segment photoluminescence quantum dot light emitting device (QD-LED) for automotive lighting systems was carried out [9] as shown in Fig.7.

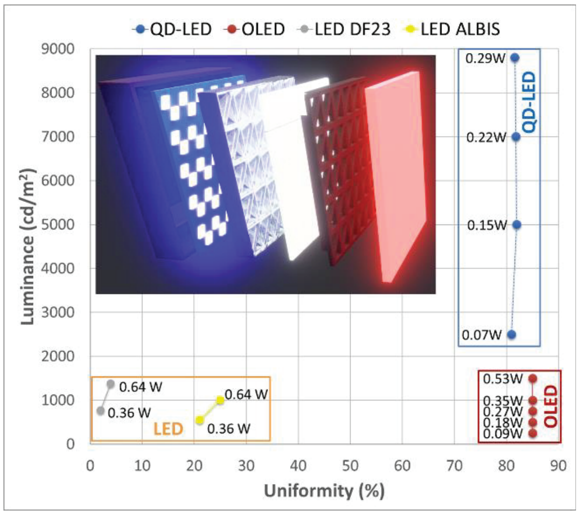

Fig. 7 Figure illustrating the QD-LED designed, OLED and LED comparison of luminance vs uniformity values [9].

The QD-LED device was fabricated using a quantum dot film (QDF), incorporating two kinds of quantum dots (QDs) synthesized to emit at 531 nm (green) and 624 nm (red). When the QDF is excited with a blue LED of a wavelength of 465 nm, a white color output is obtained. Likewise, by using different color filters, all the automotive lighting functions (interior and exterior) could be achieved [9].

In addition, an electronic control module, based on the state-of-the-art multichannel automotive lighting emitting diode (LED) drivers, was specifically designed to control each segment individually to enable the possibility of external digital communication with the vehicle surroundings. That is key to develop the autonomous vehicle by incorporating what is known as car-to-X communication, used to transmit information to other vehicles and road users through light as shown in Fig.8.

Fig. 8 Figure illustrating the digital QD-LED device designed with dynamic lighting scenario example (hazard warning mode). Car-to-X communication in rearlamps [9].

Furthermore, the low power consumption of the QD-LED device designed implies a high electrical efficiency, something critical for the electrical vehicle development. Thus, the figures of merit and performance indicators measured offer promising values to use this nanotechnology in the next future of the vehicle transportation lighting systems [9].

3 Conclusions

Quantum dots might be seen as new optoelectronic device alternatives in automotive lighting systems. As shown in the two experimental approaches based on quantum dots excitation phenomena i.e. electroluminescence and photoluminescence, both QLED and QD-LED devices are compatible with the automotive trends:

-High homogeneity and uniformity lighting.

-Car-to-X communications.

-Low power consumption: CO_2 reduction.

Finally, it is worth noting that the main current challenges to introduce this nanotechnology in the future of automotive lighting systems are based on i) the selection of environmentally friendly QDs (Cd-free QDs), ii) the efficiency of the QDs, focused on the quantum yield (QY) of the nanoparticles, iii) the reliability under an automotive environment and iv) the capability to perform accurate simulations to anticipate the optical and electrical behavior of the final device.

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