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Environmental assessment of new technologies: Production of a Quantum Dots-Light Emitting Diode

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ABSTRACT

The production of a Quantum Dots-Light Emitting Diode by Direct Laser Patterning is a new strategy to draw luminous patterns on Organic Light Emitting Diodes. The laser patterned Quantum Dots-Light Emitting Diode improves the optical performances of Organic Light Emitting Diodes introducing Quantum Dots as luminophores and avoids the use of photolithography to draw patterns, thus simplifying the manufacturing process.

The purpose of this study is to describe the production of a Quantum Dots-Light Emitting Diode prototype using Direct Laser Patterning technology and to assess its environmental performance, by means of Life Cycle Assessment method, with the aim to identify the hotspots in the production chain and to support a more environmentally-friendly product design.

The goal of the Life Cycle Assessment study is to evaluate the environmental impacts of the production of one Quantum Dots-Light Emitting Diode with a surface of 4 cm^2 and a laser patterning surface of 25 mm^2. The system boundaries were from cradle to gate and included the production of the following elements: the cadmium sulphide precursor for Quantum Dots, the organic electroluminescent polymer, the anode and cathode as well as laser patterning. Primary data were collected at laboratory scale and IMPACT 2002+ impact assessment method was used. Results show that the main hotspots are the production of the electroluminescent polymer and the indium tin oxide glass used as anode. Therefore, other materials could be used as anode and polymer with the aim to improve the environmental performances of the device. Moreover, a comparative analysis between the environmental impacts of the new patterning technology and that of the traditional photolithography shows that their environmental performances are quite similar. However, the use of the new Quantum Dots-Light Emitting Diode technology is advisable because of its better technological performance, lower costs and processing time.

1. Introduction

According to the European Commission, nanotechnologies are part of Key Enabling Technologies (KETs), i.e. those technologies which play an important role in the R&D and innovation strategies and allow the restructuring of industrial processes, thus helping to move towards a low carbon and resource efficient economy at European level as well as ensuring competitiveness (EC, 2012). Because of these reasons, the interest in nanotechnologies has increased rapidly in the last years, since they can be used for the development of new products and applications, improving their performance and offering new functionalities.

In particular, the potential applications of nanotechnologies range from new optical devices such as solid state lightening, photovoltaics, lasers, biotechnology and new textiles. Within this

List of abbreviations: Ca-Al-Ag, Calcium-Aluminium-Silver; CdS, Cadmium Sulfide; DLP, Direct Laser Patterning; FTO, F-doped SnO_2; ITO, Indium Tin Oxide; LCA, Life Cycle Assessment; LEDs, Light Emitting Diodes; OLEDs, Organic LEDs; PEDOT, [poly(3,4-ethylenedioxythiophene)]; PLEDs, Polymeric Light Emitting Diodes; QDs, Quantum Dots; QDs-LED, Quantum Dots-Light Emitting Diode; SSPs, Single Source Precursors; UHV, Ultra High Vacuum.

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frame the Organic Light Emitting Diodes (OLEDs) including Quantum Dots (QDs) are a recent area of industrial exploration in the field of flat panel displays and solid state lightening.

Quantum Dots based Light Emitting Diodes (QDs-LED) are an emerging nanotechnology which has been developed recently and may offer many advantages over conventional Light Emitting Diodes (LEDs) and OLEDs in terms of colour purity, stability and production costs while achieving similar level of efficiency (Yang et al., 2015). With the global flat-panel display market exceeding USD 80 billion in 2011 and with lighting constituting 20% of US electricity consumption, the economic and environmental incentives are clear (Supran et al., 2013).

As regards to the manufacturing process, the widely used procedures for OLEDs manufacturing include the photolithography or the ink-jet printing. The laser patterning technology has been used to transfer the active materials over a substrate and can be considered as a particular printing method, because the active layer is transferred from a sacrificial layer to a substrate by means of a laser (Wolk et al., 2004). Within the European FP7 LAMP project (Laser Induced Synthesis of Polymeric Nanocomposite Materials and Development of Micro-patterned Hybrid Light Emitting Diodes (LED) and Transistors (LET)), the laser patterning technology has been exploited in a completely new way (named Direct Laser Patterning-DLP), because the laser has been used as a means of generation of the QDs which allows the QDs-LED to be produced by direct laser writing. This approach utilizes single source precursors, which have been successfully employed in the fabrication of crystalline and stable nanoparticles (Malik et al., 2010). These molecules generate QDs through thermal treatment and they produce nanocomposite materials when used as fillers inside a polymeric matrix. If the thermal treatment is localised by using a laser source, the QDs only grow where the laser “touches” the polymer/precursor blend (Bansal et al., 2015; Resta et al., 2012; Fragouli et al., 2010; Antolini et al., 2006).

The new laser patterned QDs-LED is realised by adding a precursor within the electroluminescent polymer, which generates the QDs within the polymer by means of the action of the laser. The pattern formed by QDs is realised in just one step by using the laser direct writing. It is worth noting that luminescent QDs are produced without the use of masks and chemical processes typical of photolithography, thus considerably simplifying the patterning process.

This technological improvement (i.e. no masks and no further chemical steps) leads to an obvious economical advantage, because all costs due to masks preparation (special equipment) and chemical treatment (specific chemical laboratory suitable for substrate treatment) are replaced by the use of a single automatic and programmable machine (laser and its controller). Therefore, if considering the removal of the photolithography, the price of the laser patterned device will decrease by about 20% with respect to a conventional QDs-LED. Finally, the working time can be reduced by up to 50%.

The novelty of the proposed QD-LED patterning relies on two main concepts: i) the patterning is realised in one step by the use of laser, whereas usually in OLED production it is usually carried out by photolithography; ii) the pattern consists of luminescent QDs that are inorganic luminophores having a longer lifetime, colour purity and tenability (Mashford et al., 2013a,b; Anikeeva et al., 2009).

Considering its economic and environmental interest, the development of the new QDs-LED device with Direct Laser Patterning (DLP) requires an overall evaluation of the product's environmental impacts. In general, the environmental impact of the production of the QDs-LED should be lower than that of LED, because organic materials are used in their fabrication processes. Furthermore, soluble materials have a lower technological impact for device manufacturing (Mashford et al., 2013a,b).

Anyway, all these general evaluations should be carefully analysed and quantified to determine the environmental performance of the product, which should be assessed by a scientific and robust method, considering a life cycle approach.

This deep investigation is in accordance with the life cycle perspective recommended by both the European Commission (EC) and the Organization for Economic Co-operation and Development (OECD) for the environmental assessment of new technologies (EC, 2004) and nanotechnologies (OECD, 2013). Life Cycle Assessment (LCA) is a standardised method (ISO, 2006a,b) which evaluates the overall potential impacts of a product system, throughout its life cycle, on the natural environment, human health and natural resources. Therefore, LCA is considered as a comprehensive and powerful tool for environmental sustainability assessment and can also be used to compare the environmental performance of these emerging nanotechnologies and products with conventional technologies (Som et al., 2010). In fact, the assessment of the potential environmental impacts of a new technology, such as QDs-LED, is important from its early development stages, for a better comprehension of product's potential burdens on both the environment and human health and for supporting a more environmentally-friendly product design.

The ISO LCA method has been applied widely to nanotechnologies in the recent years, although on different products and applications and with different goals. Literature studies concern the production of carbon nanotubes (Kushnir and Sandé, 2008; Healy et al., 2008; Meagan et al., 2008; Griffiths et al., 2013), nanotitania (Osterwalder et al., 2006; Grubb and Bakshi, 2011; Babaizadeh and Hassan, 2013), cadmium selenium QDs (Sengul and Theis, 2011), carbon nano-fibre production (Khanna et al., 2008), nanopowder in plasma spray (Moign et al., 2010), nanocomposites with graphite nanoplatelets (Pizza et al., 2014), manufacturing with carbon nanotubes (Dahlben and Isaacs, 2009), nano-scale semiconductor manufacturing (Krishnan et al., 2008), high-capacity lithium-ion battery with silicon nanowires anode (Bingbing et al., 2014), nanofluid of alumina (Barberio et al., 2014). With regards to LEDs, several LCA studies have been carried out (OSRAM, 2009). Nevertheless, considering the above bibliographic review, no LCA studies on QDs-LED production have been published yet.

Therefore the aims of this paper are: 1) the description of the production of a QDs-LED with Direct Laser Patterning technology; 2) the evaluation of its environmental impacts with the Life Cycle Assessment (LCA) method; 3) the comparison of the environmental burdens between the QDs-LED by DLP technology and that by UV-photolithography. In such a way, both the environmental impacts of the materials involved in the QDs-LED manufacturing and the manufacturing process itself will be included. Section 2 includes the description of the device production, i.e. the materials, the QDs-LED technology and the patterning process, while Section 3 contains the LCA study carried out on the production of a QDs-LED with DLP, according to ISO standards and reports on the results obtained. Moreover, a sensitivity analysis has been performed on some methodological choices of the LCA modeling phase, with the aim to assess to what extent they affect final results.

2. Quantum dots-light emitting diode and direct laser patterning technology

2.1. Quantum Dots

Colloidal photoluminescent semiconductor nano-crystals, also referred to as QDs (Talapin et al., 2010; Cozzoli et al., 2006) have