Current trends and innovations

10

10.1 Introduction

For the past two decades, the optoelectronics industry has witnessed a strong growth that was fueled by the back-to-back emergence of high-profile devices. LEDs are one of the key contributors to the growth of optoelectronics market in all these years. High-brightness LEDs (HB-LEDs) have already surpassed the luminous efficacy demonstrated by the once efficient CFLs. From the beginning of the last decade, HB-LEDs have made strong sales in the backlighting systems for the displays of LCD TVs, computers, smartphones, and tablets [1]. The penetration of HB-LEDs into these applications has almost reached 100%. This compelled the manufacturers to increase the production capacity of HB-LEDs. They have also focused on improving the efficiency and quality of light as well as cutting down the costs on its production [2]. HB-LEDs have now captured the lighting market in the major sectors such as outdoor lighting, automotive lighting, digital signs, and indoor lighting.

The tremendous growth and change experienced by the LED industry have led to several new opportunities and businesses for many industries. The lowering costs, increasing efficiencies, and improving device structures have made the LED industry a leader in the lighting industry. LEDs have achieved many great strides to become an inevitable part of all the new recent technologies to make human life more comfortable and easier. They ended the realm of incandescent bulbs and fluorescent tubes in a short span of time. The LED lights meant for general illumination have got modified to deliver additional features too. The newer versions of LED luminaires are specially designed to provide a dynamic beam spread without any moving parts. This feature has found applications in the systems requiring customized control over the beam. Another modification is the removal of the external circuit board drivers that were earlier highly essential for the LED lighting systems. Traditionally, external drivers were meant for the conversion of electricity supply from the mains to a form suitable for the stable operation of LEDs. The removal of external drivers from the emerging new LED products has made them compact and the LEDs have itself become capable to handle the power requirements. Newer manufacturing processes have led to the creation of LED arrays in flexible foils. A roll-to-roll manufacturing process was found suitable for developing flexible LED displays that comprise printed electronics. The ultra-thin design of LEDs has made them applicable in various fields. Newer models of TVs and smartphones feature flexible thin displays made of such LEDs that contribute to reducing the size and weight of the device.

The Fundamentals and Applications of Light-Emitting Diodes. https://doi.org/10.1016/B978-0-12-819605-2.00010-0

LEDs are not just a mere means of lighting, but it has brought about a revolution in the life of mankind. It has touched innumerable fields of application wherein no other lighting sources were able to reach. They have captured two-thirds of the global lighting market and have extended their influence on other sectors such as display industry, horticulture, food storage, data transmission and digital communication, skin rejuvenation, and medical treatment. [3]. A number of organizations have shifted their research on LEDs citing their omnipotent applications in diverse fields. Efforts are being put to design appropriate LED products that can fit into each of the individual applications and initiate their actual commercialization for the world to enjoy a more comfortable and luxurious life.

10.2 Overview on the past and present trends in LEDs

Light has become an inseparable part of human life. Light decides how productive an individual can be at his work, how quickly he can recover from an illness, and how well he can learn. Over a century ago, people accustomed to oil lamps and candles were amazed with the popularity of the incandescent bulbs. This invention was seen as the ultimate and ideal light source. Years passed by and the society witnessed newer technologies, which were far better in efficiency and performance. Yet none were as amazing and innovative as the LEDs. In the early days of LEDs' emergence, R. Haitz made some observations and forecasted about the future of LEDs and its steady improvement accompanied by declining prices, as shown in Fig. 10.1 [4].

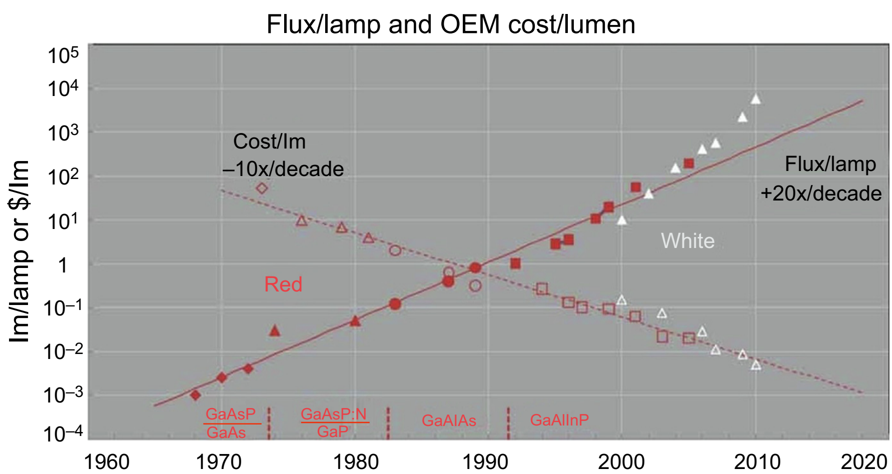

Figure 10.1 Haitz Law forecasting about the variation of light output and cost per lumen for every decade.
Reproduced with permission from Ref. R. Haitz, J.Y. Tsao, Solid-state lighting: 'The case' 10 years after and future prospects, Phys. Status Solidi 208 (2011) 17−29. doi:10.1002/pssa.201026349, Copyright. 2011 WILEY-VCH Verlag GmbH and Co. KGaA, Weinheim.

According to Haitz, the quantity of light generated from an LED will increase by a factor of 20 and the cost incurred per lumen output will fall by a factor of 10, in every decade. This trend was supposed to level off by 2016, but the improvements still continue to appear in the LED technology. Every year, LED packages come out with new streamlined mechanical and optical designs, improved electronic drivers, and enhanced performance. LED fixtures have evolved, not only in the design but also in the range of applications. LEDs have successfully found applications in diverse fields such as horticulture, food storage, dentistry, medical treatment, display devices, high-speed digital communication, and indoor and outdoor lighting, The LED lighting fixtures are becoming smarter and now, and they are not just limited to general lighting. LEDs are designed to send high-frequency modulation signals that can be picked up by a smartphone or other devices. It is, now, possible to control the color hue of the LED lamp using a smartphone and automatically switch it on/off.

Although consumers usually just want their lights to be turned on or off as per their needs, many consumers always desire to extract something more from their luminaires. LEDs have stood up to the demands of these consumers, and now, LED luminaires are twice as efficient as the ones that were introduced half a decade ago. The introduction of several new materials and technologies boosted the efficacy and performance of LED luminaires and has brought down the production costs to a considerable level. The cost of LED luminaires is now comparable to that of CFLs, and this has accelerated the adoption of LED lighting in almost every segment. Their prices have now declined to a point that every sector relies on LEDs as the most economical choice available in the market. The market potential offered by the LEDs is acting as a driving force for its development and growth. There is a rapid growth of LED lighting in the global market and the projected growth is mainly propelled by the rising demand from an ever-growing population and the progressive development of nations. The annual global shipment of LED products is projected to reach 14 billion units in the year 2022 [5]. The global lighting market is anticipated to reach USD 92.4 billion in the same year.

10.3 Innovations in the structure and designing of LEDs

To achieve a more effective connection between humans and electronics, researchers are now focusing their attention on the development of wearable electronics. This has propelled the research on the related materials like e-textile, wherein human-friendly fabrics were integrated with electronic components to provide some additional features to the human wear. A research group headed by Kyung Cheol Choi developed a fiber-based polymer LED that can be woven to create wearable fabric [6]. These fibers can be subjected to mass production just as polyethylene or nylon fibers. These polymer fibers will open the door for flexible wearable displays and lower the barriers encountered while introducing flexible wearable displays into the market. Earlier, wearable displays were produced by coating the emitting layer on a hard substrate and then attaching them onto the surface of the fabric. However, such displays were not flexible and were susceptible to damage. With the introduction of polymer fibers, it has become possible to LED displays that carry the features of a display device as well as a fabric. The light-emitting fibers were developed in the laboratory using the dip-coating process. This method involved a lot of dipping and drying and was assumed to be a more efficient process than any heat-treatment method for the application of LED fibers over small cylindrical structures. In addition, dip coating is much more effective than the inkjet printing, screen printing, or spin coating methods, as the former allows concentric coating of fibers easily. The process involved the dipping of a fiber of polyethylene terephthalate (PET) into a solution of PEDOT:PSS (poly(3,4-ethylene dioxythiophene) polystyrene sulfonate). This was, then, dried at 130 °C for half an hour. After drying, the fiber was again dipped in a bath of super yellow (poly-(*p*-phenylenevinylene) polymer OLED) solution. The dipped fiber was, then, dried in an oven and coated with LiF/Al cathode material. This process is a simple, cheap, and effective method that can accelerate the production of wearable displays. Fig. 10.2 shows the microscopic images of the polymer fiber emitting light when operated at 8 V and a bare fiber.

Currently, most of the wearable displays are fabricated using OLEDs. In most cases, OLEDs are fabricated on a glass substrate and encapsulated using a glass lid. However, the flexibility of OLEDs is lost with the use of glass encapsulation. The next generation of tablets, smartphones, and wearable displays shall be completely based on flexible displays, for which the glass-encapsulated OLEDs will not be appropriate. For such flexible displays, graphene-based ultrabarrier materials will suit the best. Graphene is granted with an excellent thermal and chemical stability accompanied by a fine carbon lattice and a densely packed structure [7]. Graphene can turn out to be an amazing barrier to liquids and gases [8]. Due to its flexibility, robustness, and transparency to visible light, it is considered as an excellent barrier film for the encapsulation of flexible OLEDs. In addition, the high conductivity of graphene acts as an added advantage in the development of graphene LEDs with more efficiency, long-lasting life, and brightness. Seo et al. used multistacked graphene films

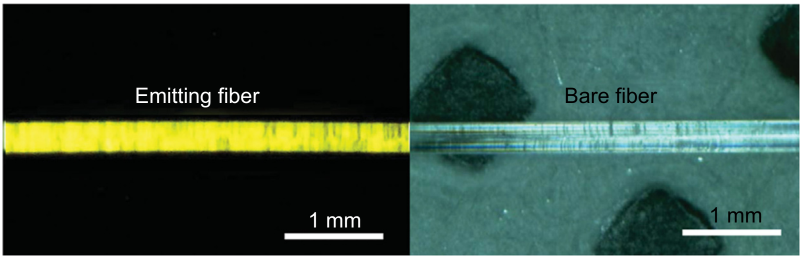

Figure 10.2 Microscopic images of the polymer fiber emitting light when operated at 8 V and a bare fiber.
Reproduced with permission from Ref. S. Kwon, W. Kim, H. Kim, S. Choi, B.-C. Park, S.-H. Kang, K.C. Choi, High luminance fiber-based polymer light-emitting devices by a dip-coating method, Adv. Electron. Mater. 1 (2015) 1500103. doi:10.1002/aelm.201500103, Copyright. 2015 WILEY-VCH Verlag GmbH and Co. KGaA, Weinheim.

with a polydimethylsiloxane buffer on a PET substrate to demonstrate a simple, low-cost, scalable, transparent, and flexible lamination encapsulation for OLEDs [9]. The graphene innovation is hugely led by the United Kingdom (UK), whose market in graphene is expected to touch GBP 800 million by 2023. The University of Cambridge, the National Physical Laboratory, the Centre for Process Innovation, and the business partner FlexEnable Ltd. have joined hands to work together on a combined project on graphene to scale-up its manufacturing landscape in the UK. They investigated the feasibility of producing graphene-based barrier films for the next-generation flexible OLED lighting and display products. Graphene is impervious to many molecules and hence, will provide significant blocking of liquids and gases, thereby enabling them to be a perfect barrier material for OLEDs. Another competitive technology that has been regarded as an appealing product for high-quality display panels and solid-state lighting (SSL) devices is the solution-processed OLEDs (s-OLEDs). The s-OLEDs have shown superior properties than the vacuum-evaporated OLEDs (v-OLEDs). The production costs involved in the development of s-OLEDs is far less than the v-OLEDs [10,11]. Burroughes et al. reported the first conjugated polymer-based s-OLEDs in 1990 [12]. Since then, several huge achievements were made in this field [13−17]. The need to achieve s-OLEDs, which are consuming a lesser amount of energy, has led to several serious efforts for the exploration of the methods and designs suitable for realizing energy-efficient s-OLEDs. Quantum dots (QDs) have also set a mark in the LED industry and are set to outperform the phosphor-converted LEDs (pc-LEDs) in general lighting. QDs have already put up a tough competition with the OLEDs in the display industry. QDs are known to produce tunable emission with low back-scattering loss. Their dominance in the display and general illumination has been long anticipated. However, they were held back due to certain difficulties in withstanding the on-chip LED temperature and photoflux intensity. The passivation of QDs turned out to be a solution to many such difficulties that hindered their path to commercial applications [18]. This resulted in the improvement of the spectral luminous efficacies of QDs way better than pc-LEDs, as illustrated in Fig. 10.3. In the case of bare QDs (nonpassivated QDs), the electrons from the conduction band can get trapped in the surface states that can decay

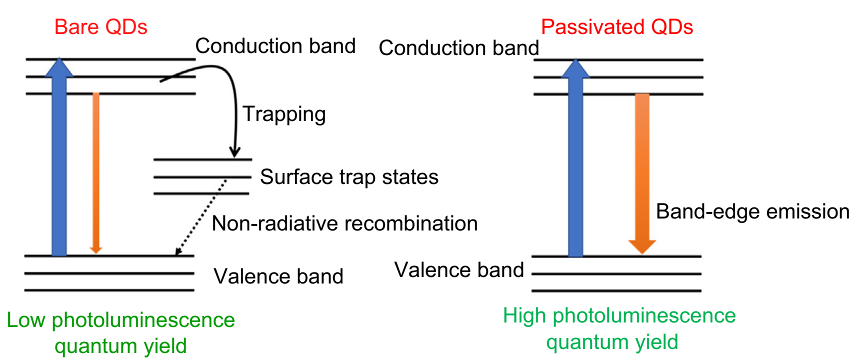

Figure 10.3 Difference in the PLQY obtained for bare QDs and surface passivated QDs.

non-radiatively to give a weak trap emission. On the contrary, QDs with the surface states passivated by inorganic or organic shells remove the occurrence of trap emission and allow only the band-to-edge emission [19]. Consequently, the photoluminescence quantum yield (PLQY) is low for the bare QDs and high for the surface-passivated QDs. In recent years, perovskite materials based on the metal halides have grabbed the attention of the scientific community working in the field of optoelectronics [20]. Particularly, hybrid organic−inorganic metal halide perovskite nanocrystals (NCs) of the form $MPbX_3$ (where M = MA [CH_3NH_3], FA [$CH_3(NH_2)_2$]; X = Cl, Br, I) have shown great potential in the luminescence industry. CsPbX QDs have also been regarded as excellent luminescent materials owing to their high PLQY. The next generation of LEDs is certainly going to adopt these perovskite materials that offer several intrinsic advantages owing to their direct bandgap. They are also known to produce high PLQY that can reach close to unity, high carrier mobility, and long exciton diffusion length [21]. The introduction of perovskite NCs for photovoltaic applications led to an epiphany that these materials can be used for LEDs too.

For an LED bulb, the driver circuit forms an integral part that converts the electricity from the mains supply into a form that can be used to operate the LEDs. Unfortunately, the driver circuits are the first ones to fail in an LED package and virtually shorten the life of the luminaire. As a solution to this, certain manufacturers have started eliminating the driver component out of the equation. Some others adopted multichannel LED drivers instead of single-channel drivers to increase device efficiency and reduce the production costs [22]. For each of the individual LED channels, the drivers can operate at different brightness levels. This enables optimization of the lighting applications as compared to single-channel drivers. LED retrofits are also a solution to reduce the maintenance costs by enabling the replacement of only the faulty components of the system, rather than replacing the entire luminaire.

10.4 Innovations in the applications of LEDs

There is a lot of buzz going on in the lighting industry with the new-found applications of LEDs. LEDs have made a strong and comprehensive presence in human life. Their suitability for applications in diverse areas has aided them to go beyond the frontiers that were never reachable by its preceding light technologies. LEDs have also paved way to achieve smart lighting solutions, wherein the luminaire can be controlled remotely just by a touch on the smartphone. LED luminaires can be connected with a smartphone, and thus, the smartphones can be used to control the lights that can be controlled. The lights can be switched on/off, dimmed, and its color hue can be varied as per the need. The biggest potential benefit of this feature is the greater energy savings attained by the smart utilization of the light. In commercial airlines, passengers often experience jetlag during their international travel across the longitudes of the earth. As illustrated in Fig. 10.4, the aircrafts are installed with color-tunable LEDs to provide comfortable lighting to the passengers and make them adjust with the jetlag faced while traveling to different time zones.

Figure 10.4 Color tunable aircraft cabin-lighting.

Apart from smartphones, LED luminaires now offer the ability to connect with the Internet of Things (IoT). The term IoT is usually meant for describing the set of gadgets (in addition to computers or smartphones) that are connected with the networking web. Thus, all sorts of household equipment such as fridge, air-conditioners, TVs, and lamps can be included in IoT as they can be connected to the internet. The best way to connect all the things at once is through the ideal network provided by lighting. As light fixtures are already installed on the ceilings and walls of a building, it is easy to connect them to all possible things on which light will fall on. The only requirement will be the additional installation of some sensors and a data connection. Commercial outlets, museums, indoor spaces, railway stations, and airports are all transforming into internet hubs, and this will be further facilitated by the new Li-Fi system. The smart lighting feature of LEDs enables them to operate the Li-Fi system and connect all the things to a single network. These light bulbs are becoming smarter and can be controlled by voice commands too. LIFX, a pioneer in smart LED lamps, has collaborated with Google to add voice controls for the LED lamps through smartphones or other devices that run on the Google's Android operating system. The voice commands can control the lighting system connected to it through the LIFX app or can be controlled using Google without the app. The lights can be switched on or off, and the lamp's color hue and brightness can be adjusted just by giving voice commands on the Android device. The Android device must be always kept connected to the network for enabling the voice command feature. Philips Hue is another android app that has been introduced to control the lighting system. Fig. 10.5 illustrates the LIFX app and Philips Hue app.

LEDs have made promising future for the horticulture and indoor farming. These innovative sources of artificial lighting have improved the nutrient quality in plants, microgreens, and sprouts [23]. LEDs not only provide supplementary illumination for plants but may also prove to be useful sole-source lighting at times when no other light source (including solar energy) is available. The exposure of sprouts and microgreens to the LED source can help in the regulation of a series of structural genes in them. These are of utmost importance for the biosynthesis of phytochemical compounds such as carotenoids and flavonoids. It is predicted that the number of greenhouses and horticulture farms depending on LED light sources will be on a

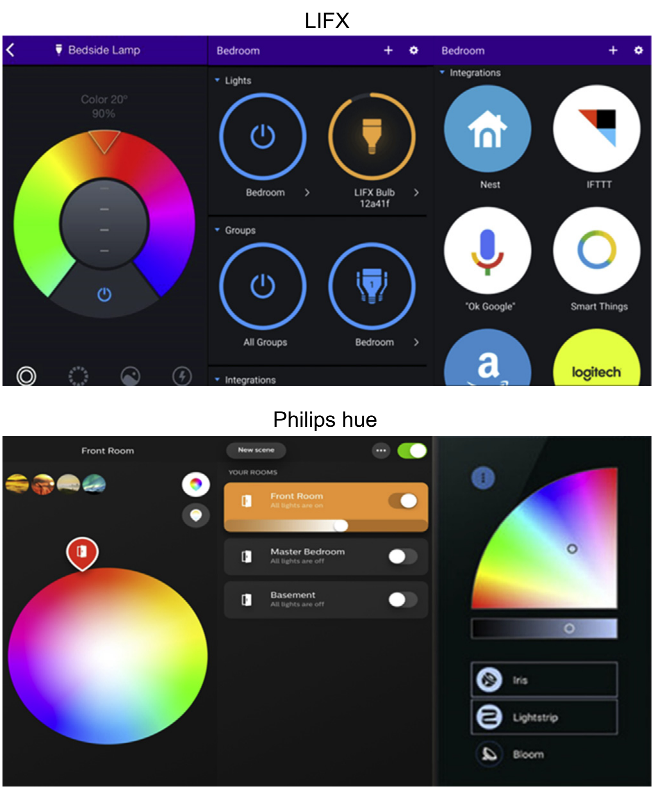

Figure 10.5 Android-based LIFX and Philips Hue apps for controlling the LED lighting system.

rise [24]. The introduction of LEDs into the food industry has provided huge health benefits and opened up possibilities to produce enough grains and vegetation to sustainably feed the ever-expanding population.

10.5 Innovations in fashion

The best way to express fashion in society is through the clothes worn by an individual. The fabric materials used for clothes are meant to be both seasonal wear and attractive. Gone are the days when people used to prefer clothes just on the basis of fashion. The modern era demands something extra in addition to fashion. Swedish designer, Malin Bobeck, made efforts to bring life into the fabrics by inducting LEDs into them. She created a glowing fabric by weaving optical fibers in them. She developed a grand textile of wonder by incorporating 500 programmable LEDs into the fabric that responded to human touch. Several other textile industries experimented by developing jackets and coats embedded with LEDs. They are also embedded in the skirts for ladies and girls to light up their thighs and give a more fashionable appearance to the user. Depending on the movement of the user, the LEDs change colors with the help of gyro sensors that keep track of the user's movements. The gyro sensors are miniature in size that is capable of sensing even the rotational movement of skirts. Consequently, the skirt shows different patterns and colors of light, thereby giving a vivid appearance to the skirt. Another wonderful piece of LED skirt was launched by ThinkGeek, a US online retailer. They named the skirt as "Twinkling Stars Skirt" because of the fancy pattern of LED lights that twinkle like a star constellation as shown in Fig. 10.6. There are more than 250 LED lights embedded within the blue skirt to mimic the star constellations. There are three layers that give a fascinating appearance to the skirt. The layers include the white liner, the gauze layer, and the

Figure 10.6 "Twinkling Stars Skirt" created by ThinkGeek.

transparent constellation layer. The battery-powered LED lights are attached to the gauze layer that consists of 30 elastic snap tabs. The battery pack is held within a built-in pocket in the gauze layer. The blue skirt can be worn with the lights on or off. If the battery pack is removed, it becomes just like a regular skirt. However, when the lights are powered on, the 45 feet of the LED strip will shine within the layers to appear like fairy lights twinkling through the fabric.

Apart from the fancy appearance for fashion, LED clothing has also been brought to certain life-saving applications. LED embedded apparels are recommended for cyclists at night to prevent them from accidents. The National Highway Traffic Safety Administration (NHTSA), a US federal agency, has reported that the number of cyclists dying due to accidents has increased particularly because they are not visible to other vehicle drivers at night. The Centers for Disease Control and Prevention, a US federal agency under the Department of Health and Human Services, recommended the cyclists to wear apparel with active lighting and reflective panes. Visijax, which is a leading company in the world for the production of wearable electronic apparel and clothing, has developed a coat with LED lights embedded on the back of its sleeves. The lights would flash whenever the cyclist wearing the coat would lift his arm to signal his turn and thereby, alert other vehicle drivers on the path or behind the cyclist. A narrow strip of red LEDs is also embedded at the back bottom of the coat to mimic like a brake-light. However, the coat is incapable of sensing the braking of the cycle and hence, the red strip of LEDs is a mere indicator of the presence of the rider. A line of apparel embedded with smarter LED lights was developed by Lumens. When the lights are not on, the jacket looks like a regular, fashionable one. These LED lights are customized to conduct several functions in the jacket. Lumens app, which is available in both Android and iOS versions, can pair with these LED lights and perform several actions. They can be configured to use GPS navigation through Google Maps and the gyros with the help of this app. The jacket worn by the cyclist can give signals of his movements to other vehicle drivers and warn them about the cyclist's next move. For example, the jacket shall stimulate a red brake light when the cyclist stops, flash an orange light to signal his turn, and switch on the strobe mode while crossing an intersection, as shown in Fig. 10.7. The lights can also be customized to indicate different activities of the wearer. Another British brand, Lumo, has also introduced a wide range of apparel and backpacks with built-in LEDs. The LED lights on the clothes may go unnoticed during the day but will never miss any admirers during the night. As per Lumo's claims, these LEDs are visible from a distance of 400 m in the dark. Other added advantages of these clothes are that they are stain-resistant, waterproof, and can be machine-washed. The LED lights are powered by a light-weight rechargeable battery that can last for 2–6 h on a single charge. Lumo's Herne Hill Harrington jackets boast of bike-friendly features that consist of a dropped tail, stretchable shoulders, and inner cuffs capable of resisting the entry of cold air. This range of apparel also includes a polo shirt with white LEDs (WLED) in the front placket and red LEDs at the back seam. The Bermondsey backpack is decorated with WLEDs on its straps and red LEDs on its back. Impulse has also created a jacket to increase the rider's

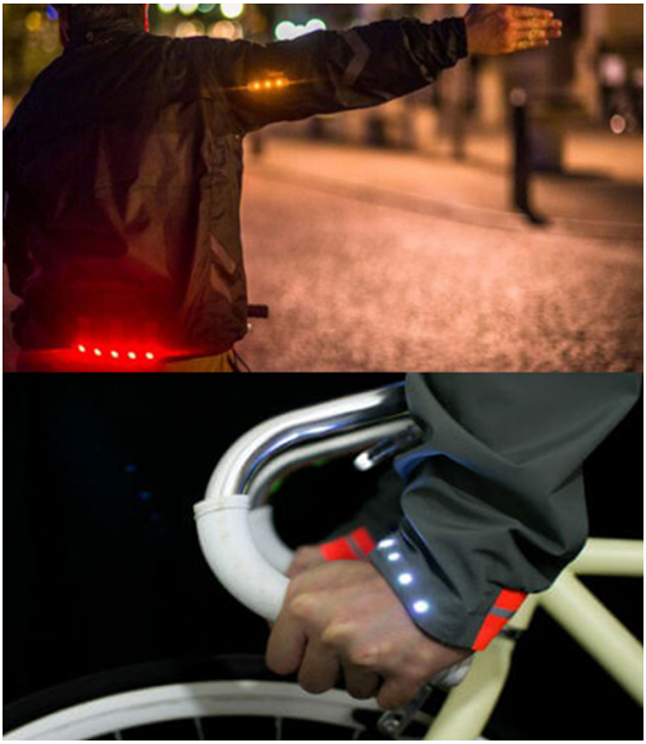

Figure 10.7 Jacket embedded with LEDs for the cyclists.

visibility to other vehicle drivers through the illumination of its high-output LEDs. These jackets offer a wireless link with the motorcycle that aids in stimulating the illumination of certain LEDs based on the movement of the motorcycle.

LED lights have also been embedded in clothes to detect the Wi-Fi and Bluetooth signals in the nearby premises. Matt Martin created a perfect shirt with a combination of electronic devices powered by Li-polymer batteries to detect the Wi-Fi and Bluetooth signals. 31 Neo pixel strips comprising more than 100 LEDs were hand sewn into the shirt. LED-embedded goggles are another piece of innovation that combines the utility with fashion. The implantation of LEDs into swim-goggles has facilitated swimmers to swim from one end of the swimming pool to the other in a straight line. The goggles are easy to use in water. They are powered by high-precision compass, accelerometer, and a microprocessor. To set the target destination, the user needs to look at the far-off target and switch on the button by pushing it on the side of the goggles. This will set the target and the swimmer can swim to the destination under water. If the swimmer is swimming correctly in the direction of the destination, then the two LEDs situated above each eye of the goggles will illuminate green. If the swimmer strays away from the destination or follows a wrong path, then the LEDs will illuminate yellow or red light depending on the level of straying. After reaching the target destination, the swimmer can set a new destination by looking at the new target and pushing the button again.

10.6 Current scenario of LED market

Manufacturers have explored the potential for LEDs by introducing new lighting designs and producing the luminaires as per the requirement of the situation in which it is to be mounted. Special care has been taken to optimize the lighting needs and provide the best experience to consumers through integrated lighting. LEDs have achieved great heights by meeting the demands of the consumers in terms of the efficiency, color tone, and operating life. Although there is seemingly little room left for improvement, LEDs continue to amaze again and again with its new developments that pushed its performance limits.

Recently, UV-LEDs have gained huge popularity owing to its disinfecting properties. The rising number of bacterial and viral infections/diseases has provided an urge to disinfect the surroundings. Of late, the mayhem caused by the COVID-19 disease has increased the demand for disinfection. The continuing global spread of the disease has fueled great concerns over the future and this has increased the need for sterilizing. Consequently, the sales for the UV-LED products have gone up significantly. Several Chinese automotive companies have relied on the UV-LEDs to develop sterilization systems for the vehicle's interiors. UV-LEDs are also used by space research centers like NASA to provide a germ-free environment for astronauts aboard the International Space Station. One of the major developments in this technology is the improvement in its lifetime. Earlier, UV-LEDs were highly expensive and offered a short lifetime of just 10,000 h. This disheartened many manufacturers and they refrained from the production of UV-LEDs. However, a South Korean company, Seoul Viosys Co. started developing Violed UV-LEDs that offered a higher lifetime of 50,000 h. They claim that 1 min of UVC exposure using UV-LEDs can sterilize about 90% of the coronavirus and 97% of the influenza-type viruses [25]. Everlight has also designed a 280-nm emitting UVC LED that can kill pathogens effectively. These LEDs are packaged in inorganic quartz and can be mounted in direct contact with the water, thereby, making them eligible to disinfect the drinking water more efficiently. The US Department of Energy's Ames Laboratory has developed an OLED that can emit near-ultraviolet light [26]. These OLEDs could emit light in the wavelength range of 370–430 nm.

The market trend for the LEDs has always been ascending since its penetration into the lighting and display industries. Although LEDs were priced much higher than their counterpart technologies, their efficiency and longer lifespan compensated for the initial investments [3]. There has been a rise in the LED market at a global level. It is projected that 67% of the energy will be saved by the year 2030 with the implementation of LEDs [27].

Unfortunately, there has been a down graph in 2020 in the market for packaged LEDs in overall. Compared to its preceding year, the year 2020 witnessed a decline of 4% in the market for packaged LEDs. There were a plethora of negative factors that resulted in this scenario. There was an oversupply of LEDs in the late 2018 that led to a drop in the prices during the first quarter of 2019 and the situation worsened further with the price erosion of LEDs in mid-2019. This led to a significant drop in LED prices during the fourth quarter of 2019. Compared to the fourth quarter of the previous year, the mid-power LED price dropped by 20%−30%, while the prices of high-power LED dropped by 5%−10%. The overall decline in the revenues of the LED market for 2019 was about 4% than the previous year. Another factor that put a dent in the LED market was the US−China trade war. It was anticipated that the repercussions of the trade war will be sorted out in 2020 and the LED market will resume its recovery with the pickup in its demand. However, things got worse with the outbreak of the corona-virus disease (COVID-19) in December 2019. It is still not clear how the pandemic will impact the LED business in 2020 and the succeeding years. The year 2019 also witnessed the shutting down of many troubled manufacturing companies that were later acquired by the giant players such as Signify, GE, and Acuity; yet, the manufacturers are optimistic that the LED market will gain positive momentum and recover all its losses incurred due to the global crisis. By 2024, the LED market is expected to show 5% growth to reach the revenues of $20 billion. Huge growth is anticipated in the sales of mini-LED and micro-LED based displays. This sector earned $200 million revenue in 2019 and is expected to grow to $1.6 billion by 2024. The 5-year forecast predicts that the revenue of the initial 3 years will be mainly contributed by the mini-LEDs that would serve as backlighting for displays in a more fashionable way than the present displays. The last two years of the forecast will be mainly dominated by the self-emissive displays developed from micro-LEDs.

10.7 Limitations and challenges

LEDs have become the backbone for the SSL industry and many other related sectors. LEDs have successfully overcome most of the limitations faced by the previous lighting sources. Some of the advantages accompanied by the LEDs were the superior color rendering ability and spectral output, higher efficiency, longer lamp life, lower power consumption, etc. All these attributes made LEDs distinct from other lighting sources and hence, LEDs became the most desirable lighting technology. Yet, certain limitations put LEDs on the back foot at certain points. The LED industry has made massive strides in growth and processing technologies. Regardless of the breath-taking progress made by LEDs, there are still certain issues that require further improvement. The performance and reliability of LEDs are sensitive to the temperature and other environmental conditions. In addition, there are certain challenges faced in the cost-control during production and thermal management. LEDs exhibit optimum performance in the ambient temperature of the operating environment. In high-power LEDs, this feature is highly critical. In recent years, there has been significant improvement in the energy efficiency of LEDs. Yet, there has been a lot of heat dissipation from LED packages mainly because of the electronic drivers installed in them. LEDs can be permanently damaged if they are exposed to heat very often. It may also result in the degradation of the LED's performance, decrease in the quality and quantity of the light output, or premature failure of the device. It is highly crucial to provide proper heat sink or cooling systems to the luminaires to ensure proper heat dissipation. This would guarantee a long lifetime for the LEDs and allow its operation in a wide range of temperatures. The involvement of heat sinks in the LED package is one of the prime reasons that the manufacturers are facing difficulty in bringing down the production costs of the LED. Heat sinks are unavoidable components of the package and are essential to curb the problem of overheating. Generally, materials with high thermal conductivity are used to propagate the heat out of the package. However, these materials come with a substantial amount of weight and cost. As a result, the weight of the LED package increased along with its cost. Additionally, the higher weight of the package means that the cost of shipping the LED products is also raised. An LED package generally consists of three features [28]:

(a) Heat generation and dissipation
(b) Fluid flowing and molding
(c) Lighting extraction and control.

The first two features strongly influence the lighting extraction and control of the LED package. The heat generation in the LED package can arise from multiple reasons. The prime reason for the generation of heat in the package is the non-radiative recombination processes in the LED chips. In addition, the driver circuits add to the overall heat generation in the package. The phosphor coated on the chip is also affected by the heating of the LED chip. The heat generated in the chip will be conducted by the phosphor coating, and during operation the phosphors themselves can generate additional heat. A phosphor is coated on the chip by embedding them in a silicon matrix. The phosphor can be considered as a non-Newtonian fluid that also exhibits the flowing processes of contacting, wetting, spreading, and stabilizing [28]. When a phosphor gel is dispensed over the LED chip, it makes a contact with the chip and wets it to cover the chip. The phosphor spreads over the heat slug and then stabilizes over the chip to form a convex shape. However, the phosphors particles can form non-uniform distribution on the chip as a result of gravity. The non-uniform distribution of phosphors can adversely affect the optical characteristics of the LED package [29,30].

Sometimes, flickering and other visual anomalies are observed in LED lamps, which appear due to the occurrence of large ripples in the DC power supplied to the lamps. The temporal variation in the power supply causes flickering in the lighting. When an unbalanced current waveform is supplied to the LED, flickering happens. The LED drivers supply a regulated power supply to the LEDs from an AC power input. The regulated power supply provides a stable and balanced power for the LED to operate. Any kind of instability in the power supply would result in the LEDs to flicker indicating a malfunction in its operation. It is a challenge to develop appropriate driver circuits and power supplies for an LED that can avoid the flickering of light from the LEDs. The glare from the LEDs remains to be an obstacle, which must be addressed by the manufacturers to improve the overall lighting experience. LED lights are also facing certain challenges in the automotive lighting sector. WLEDs have found suitable applications in the automotive forward-lighting applications. Although their mechanical packaging and thermal resistance were appropriate for this purpose, their luminance and luminous flux remain a matter of concern. Still, high-intensity discharge (HID) lamps show higher luminance and luminous flux than the LEDs. The LED headlamps are now just limited to the premium model cars due to their high pricing.

10.8 Future prospects and scope

The new decade has ascended with higher aspirations and planning to tackle the newer challenges in the lighting industry. The industry has experienced rapid digitalization and dazzling transformation to exhibit some key advances in the technology due to which the SSL industry will touch the greatest heights in the next 10 years. The manufacturers are trying to take advantage of every opportunity by designing the LED products with the involvement of the latest technologies that are at their pike. The LED industry has gone through certain ups and downs in the recent past. However, in the long run, LEDs have proven a profitable track and will keep continuing to do so. LEDs have successfully penetrated various sectors such as automotive lighting, traffic signals, communications, signage lighting, medical sector, horticulture, and food industry. However, its main objective was to dominate the general lighting sector and to eliminate the existence of incandescent and fluorescent lamps. The emergence of LEDs has not only lowered the energy consumption but also reduced the carbon footprint. The whole new range of applications is now driven by the new LED technology that has presented a novel approach to the lighting products.

During the early days, there used to be a belief that LEDs are not meant for every application. However, things have changed and now LEDs have spread their wings in almost every field. Some fields have adopted LED technology a bit slower than others, but this did not halt the penetration of LED technology in those fields. Rather, the old technologies were forcefully thrown out by the consumers who were overwhelmed by the richness of the LED technology. Nowadays, everything is turning wireless and eliminating the long tangling wired connections that often resulted in a mess. The lighting controls are also not an exception and they are slowly approaching the wireless trend. Wireless communication devices such as tablets or smartphones can be used to control the luminaires and set the desired color hue. The retrofit modules of LEDs are the most appealing as they eliminate the need for replacing the entire luminaire and just concentrate on the replacement of the faulty component of the module. In short, LED luminaires are transforming into plug-and-play devices that do not require a professional electrician to come and replace the faulty luminaire.

10.9 Conclusions

It is a daunting task to predict the position of LEDs or SSL in the next 10 or 20 years. However, identifying the present conditions as clues to the future, it can be assumed that LEDs will head-on to become the prime technology for lighting and other related applications. The rise and popularity of LEDs have helped in the cause of lowering their prices and making them easily available in the market. The boundaries projected on the LED efficacy and costs by the Haitz's law have been shattered long back. One of the reasons for the LEDs exceeding the limits set by this law is the incorporation of phosphors into the device structure. Phosphors have become an integral part in the fabrication of WLEDs. The innovations introduced in the design and applications of LEDs have grabbed global attention. Despite the present global economic conditions, the LED market has maintained its vibrancy. It has not only established a strong position in the market but also eliminated the existence of its rival technologies. Although there are certain limitations and issues, LEDs hold the ability to overcome them and emerge as a flawless technology very soon. Owing to the rapid improvements in the mechanical, electrical, optical, and thermal components, it is guaranteed that the LED technology will advance rapidly to reach the pinnacle very soon.

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