Advanced light emitting diodes structures for optoelectronic applications

J. Kovac*, L. Peternai, O. Lengyel
Department of Microelectronics, Slovak University of Technology, Ilkovicova 3, Bratislava 812 19, Slovak Republic

Abstract

This review summarises the recent progress in development of advanced high brightness and white light emitting diodes (LEDs) that have been reported by several laboratories. Two main orientations in LED fabrication based on inorganic and organic semiconductor materials are described. LEDs offer a number of advantages compared to existing light sources in optoelectronic applications. These include increased lifetime, reduced power consumption, higher brightness and better spectral purity.

Keywords: Light emitting devices; HB LEDs; White LED; OLEDs

1. Introduction

Nowadays, one of the most important part of optoelectronic devices are light emitting diodes (LEDs), because several factors are driving their development. The most important ones are brightness, efficiency, flexibility, lifetime, rugged construction, low power consumption and suitable driving voltage. These properties are contributing to growth in markets such as traffic lights, automotive brake signals displays, decorative signs and the many uses of the new white LED-based products. Conventional LEDs include GaAsP (yellow to red) and GaP (green to red) devices. A new development is directed to various materials used for high brightness (HB) LEDs based on AlGaAs (red), AlInGaP (yellow-green to red) and InGaN (blue, green and white) devices. The development of LEDs is dependent on epitaxial growth advances in compound semiconductor technologies, mainly molecular beam epitaxy (MBE) and metal-organic vapour phase epitaxy (MOVPE).

Organic LEDs (OLEDs) have undergone dramatic improvements in performance in the last fifteen years. Two main types of OLEDs either based on conjugated polymers, or small-molecular-weight materials have emerged. The organic materials require different technologies such thermal evaporation or spin coating. The electrical, mechanical and thermal properties of organic semiconductor materials are different from those of inorganic semiconductor materials.

2. LED’s evolution

The first LED was developed in the sixties based on GaAsP layers, by Holonyak [1]. It emitted red light with very low performance approximately 0.1 lm/W. The evolution of LEDs called ‘Craford’s law’ is illustrated in Fig. 1, which shows of about tenfold increase in light output performance per decade [2,3]. In the 1970s first light emitting diodes were discovered with green, orange and yellow light. In the past different colours of LEDs with low efficiency of the emitted light were created by using filters (epoxy dome). Progress in blue light emission development was in 1993 [4,5]. The worldwide interest in the field of organic electroluminescence starts after development of thin film double layer organic light emitting device (OLED) by the Tang and Van Slyke (1987) in the Eastman Kodak’s research laboratories [6]. The first polymer OLED device in 1990 [7] has followed this device based on small-molecular-weight materials. The LEDs market segment has phenomenal increase, after development of high brightness (HB LEDs). For the last five years, the HB-LED market has grown by over 50% per year, from about US $100–200 million in 1996 to US $1.2 mld in 2000 (today HB LEDs represents 42% of the LED market) [8]. Incandescent lighting sources, first developed by Edison, still consumed roughly a third of the energy for lighting. Jeff Nelson from Sandia Laboratories says: ‘If all the
incandescent and fluorescent bulbs in the world were replaced with LEDs, it could save the equivalent of 38 nuclear power plans [9].’ This trend is well documented in traffic light market. The standard incandescent bulb traffic light with colour filter can be replaced by HB LED with nearly ten times smaller power consumption depending to the light colour.

3. High brightness LED (HB LEDs)

Development of \text{AlGaInP} and \text{AlGaInN} compound semiconductors and their ternary and quaternary alloys incorporated in LED structures rapidly increased in the last few years. Recently, fabricated LEDs using double heterojunction (DH) or multi quantum wells (MQW) active layers increased their efficiency several times. Development of HB LEDs is roughly divided into two main orientations: first using \((\text{AlGaInP})_x\text{GaAs}_{1-x}\) active layer lattice matched to GaAs (covering amber to red colour) and second \(\text{GaN/InGaN}\) nitride based technology (covering blue to green colour). LEDs using AlGaInP quaternary alloy were developed in the mid 1990s using GaAs substrate and their performance reached values of approximately 12 lm/W. Disadvantage of this substrate is its non-transparency for visible light, which results in photon absorption by substrate. To resolve this problem wafer bonding technique was used as shown in Fig. 2. In the wafer bonding technique, after selective etching of AlGaInP epilayers, the highly transparent GaP substrate \((\text{TS})\) is placed in contact [10]. Slight pressure is applied to wafer pairs and bonded area spreads laterally across whole wafer. GaP has transmission above 60% for wavelength range over 560 nm. Changing absorbing substrate to transparent doubles, the flux output from the same epitaxial structure and external quantum efficiency increased by up to 30% at 632 nm [11].

Hewlett-Packard has developed a different shape of previously mentioned LED structure called truncated-inverted-pyramid (TIP) [12]. The performance of TIP LEDs reaches 100 lm/W for amber light. This brings eight times increased luminous flux vs. firstly mentioned GaAs system and increase of external quantum efficiency up to 50%. When the AlGaInP active layer emission wavelength is reduced to green region, the luminous performance drops sharply because the band structure of AlGaInP approaches the indirect region as illustrated in Fig. 3.

Development of nitride based structures for blue to green colour and massive rising of performance, made them widely used and much cheaper. GaN, AlGaN and InGaN layers are grown by MO VPE on sapphire or SiC substrate as shown in Fig. 4. The active In\text{Ga}_{1-x}\text{N} layers cover the band-gap energy in the range of 1.95–
3.4 eV. All structures include buffer layer, because interface between substrate surface and nitride layers contains many dislocations, (the lattice mismatch is 3.5% for SiC and 13% for sapphire) [13]. Sapphire is inexpensive and highly transparent, while SiC gives many advantages from the epitaxial growth and device processing point of view [14]. Major development is concentrated to increase the brightness of nitride based LED devices from about 15 lm/W today to 50 lm/W over the next half decade. The longest peak wavelength of the InGaN based LEDs achieved the range of 500 nm (blue-green), because the crystal quality of InGaN active layer becomes poor when the indium mole fraction is increased in order to obtain a green band emission [3]. The main goal in nitride technologies is to increase performance above 100 lm/W and to use blue HB LEDs as a basic light source in high brightness white light devices. Another perspective alternative for GaN devices may be to use rare earth dopants (Eu, Er and Tm). Rare earth doping of GaN has led to a new full colour thin film electroluminescent (TFEL) phosphor system. GaN films doped with Eu, Er, and Tm dopants emit pure red, green, and blue emission colours, respectively [15].

4. Organic light emitting devices (OLEDs)

Since the first observation of light emission from OLEDs, they have been studied extensively. The large number of organic materials and structures has been used in order to improve the device properties. In the simplest configuration, the active organic layer is sandwiched between the two injected electrodes, one of, which is transparent and placed onto a glass or plastic substrate. The common material for transparent anode is Indium Tin Oxide (ITO), which has a suitable combination of conductivity, transparency and high work function. The small difference between the work function of electrode and appropriate energy level of organic materials necessary for the effective charge carrier injection. The metals with low work function such as Ca, Al, or alloy of Mg:Ag are used as a cathode. In the first polymer OLED, the single layer of PPV poly(p-phenylenevinylene) has been used [7]. The other typical polymer materials are PPP poly(phenylene), PT (polythiophene) etc. The single layer devices have generally smaller quantum efficiency, because of organic materials that have mostly large disparity between electron and hole mobility. This causes the location of recombination zone nearby the organic–electrode interface and gives rise to quenching effect. This obstacle could overcome in the double and multilayer configuration of OLEDs, where materials with specific transport and emission properties are used. The typical double layer configuration consists of the hole injection contact, hole-transport layer, electron-transport layer and electron injection contact. The widely used small-molecular-weight hole-transport materials are NPB (4,4'-bis[N-(1-naphthyl-1-)N-phenyl-amino]-biphenyl), and TPD (N,N'-diphenyl-N,N'-bis(3-methyl-phenyl)-[1,1'-biphenyl]-4,4'-diamine). The best-known small molecular weight electron-transport active light emitting material is Alq3, (tris-(8-hydroxy-quinoline) aluminum). By doping the active layer with a few weight percents or less of proper dopant, the host emission could be changed to the dominant dopant emission [16]. The dopants are mostly the fluorescent dyes with red shifted emission relative to a host. The OLEDs with proper amount of the dopant dye molecules showed the higher output efficiency in comparison with undoped [17]. This phenomenon is attributed to the efficient energy transfer from host to the dopant and reduction of self-quenching mechanism. The further improvement of operational
conditions involves even more complicated multilayer device [18–20] configurations as shown in Fig. 5 and utilizing a phosphorescent molecules [20,21]. The additional individual layers have specific functions such as to improve injection contacts for achievement of better hole and electron balance, to block charge carriers, to locate and improve the probability of recombination, to separate the charge transport layer and emission layer etc. Dissimilar the inorganic LEDs, they can be fabricated on the manifold even the flexible substrates. The low cost of materials and fabrication processes is a promising factor, when the aim is a mass production. The polymer based OLEDs can be fabricated by the cheap spin coating technology [6,16] and the small-molecular-weight devices are fabricated mostly by the thermal evaporation [6,16,17]. The other promising technology, such as ink jet deposition or printing can be used [22]. Apart from criterion of efficiency, the lifetime and stability of devices is most important. The organic materials react with moisture and oxygen and for the reliable operation are sealed in the inert gas atmosphere. The recent improvements have taken OLEDs to luminous efficiency greater than 60 lm/W [20,21], lifetime in excess of 50 h [23,24] and driving voltage below 5 V. The most impressive start of OLEDs is on the portable monochromatic and full colour displays market for small applications like car stereos, mobile phones and personal digital assistant (PDA) displays, where the first devices are commercially available [25]. The OLEDs are self-emitters, which means that unlike liquid crystal displays, they do not require back-lighting and can be very thin with low power consumption. By the prognosis of the US industry analyst Stanford Resources the global market for OLED displays will hit USD 2.3 mld in 2008.

5. White LEDs design

Against the backdrop of a rapidly growing market for high brightness LEDs of all colours, white light emitters have attracted special interest recently for a host of potential applications in cars, traffic information signs, displays and general illumination. Although the output of red, green and blue LEDs can be combined to produce any colour including white, a more hopeful method for producing white light is to combine a blue LED with a fluorescent converter, which emits a broad spectrum at longer wavelengths. The combination of InGaN HB LEDs with a fluorescent converter material results in white LEDs with efficiencies exceeding 10 lm/W [26]. One of the most important steps in the development of white LEDs will be to fabricate devices, which utilise UV emitters as the primary light source combined with a converter materials, which absorb 100% of this UV radiation, and re-emit across the whole visible wavelength range.

White light can be produced in the OLEDs by the combination of the proper dopant [16]. Unfortunately, many white OLEDs suffer from voltage dependent variation in emission colour and small efficiency [27]. Nevertheless, the intensive research promises further improvement in this area. White LEDs are facing a big challenge—huge market, mainly in general illumination. The Fig. 6 shows technology roadmap, which illustrates the increasing tendency of white LEDs performance and

---

**Fig. 5.** Schematic structure of OLED.

**Fig. 6.** White LED market prediction [7].
penetration into the light market (above 17%) for the next decade and decreasing tendency of price per luminous flux to 37 lm/$ [8].

6. Conclusion

The major advantage of LED applications is their low power consumption and the fact that they work at low level voltage with high brightness. Recently, brightness of colour LEDs outmatches brightness of bulbs with additional colour filter. For colour applications, LEDs has chance in the near few years’ trade out other light sources with filtration. The big challenge is waiting for white light emitting diodes, to increase performance above 80 lm/W to become competitive with fluorescent lamps. White LEDs will have a great and wide market in public, indoor and architectural lighting. The question is, which will be a better choice: using three colours (three diodes) for mixing with a task to produce spectrally pure white light or using blue (UV) LED embedded in converter material to create white light. The first choice is suitable for colourful outdoor displays, while second one for previously mentioned lighting. LEDs offer a number of advantages compared to existing light sources. These include increased lifetime, higher brightness, better spectral purity, reduced size, and power consumption.

Organic based LEDs successfully raid the way in full colour display applications for costumer electronics like digital cameras, cell phones, car stereos, personal digital assistants or monitors. Their great advantage is that they are self-emitters, need less energy, can be formed into different shapes and can be much thinner as LCD devices. If they are grown on a plastic substrate, they are flexible too.

The future of LEDs is clear: more colours, more brightness and low energy consumption.

Acknowledgments

The described work was possible thanks to the support of The Slovak Grant Agency project No. 1/0152/03 and IST-2001-32793 ‘VGF GaP LEDs’.

References