High Brightness LEDs: Manufacturing and Applications

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Abstract

In this presentation an overview about the LED technology is given containing the functional principle, the basic production steps epitaxy, chip technology and packaging as well as solutions for white light of different color temperature and quality. The paper will also include the current status of the performance data and an overview on the actual and near future applications for LEDs. The key challenges for LED manufacturing will be highlighted.

INTRODUCTION

High brightness LEDs based on the InGaN and AlInGaP material system gained enormous importance in the last two decades in various application fields like automotive, consumer and solid state lighting. The main advantages compared to conventional light sources like bulbs, halogen lamps and fluorescence lamps are the high efficiency and lifetimes of over 50000 hours. Furthermore LEDs enable more design freedom for illumination applications due to their small size, dimming ability and the possibility to realize a wide range of colors. The rapid increase in efficiency of light generation to over 50% enabled a huge market potential. To meet the market requirements a key goal next to further increase the efficiency is to lower the production costs and a fast growth of production capacity.

FUNCTIONAL PRINCIPLE

As shown in figure 1, a LED consists of a few µm thick, crystalline compound semiconductor layer (epitaxial layer) on a conductive substrate. The electrical connection of the LED is realized by metal contacts on the substrate backside and on top of the semiconductor layers. There are also LEDs on isolating substrates where both contacts are places on top of the diode. The compound semiconductor layers are doped to build a pn-junction. During operation, holes and electrons as carriers are transported via the metal contacts towards the pn-junction which is also called active region consisting of a multiple quantum well with a thickness of about 100 nm. The injected carries are collected in the quantum wells where a radiative recombination of electron-hole-pairs takes place. The composition of the material in the quantum wells of a few nanometers thickness defines the energy gap and therefore the wavelength of the emitted photons. The ratio of emitted photons per injected electron-hole-pair is the internal quantum efficiency which ideally should be 100%. Appropriate materials for light generation in the visible spectral range are compound semiconductor materials like AlInGaN (blue/green) and AlInGaP (yellow, orange and red).

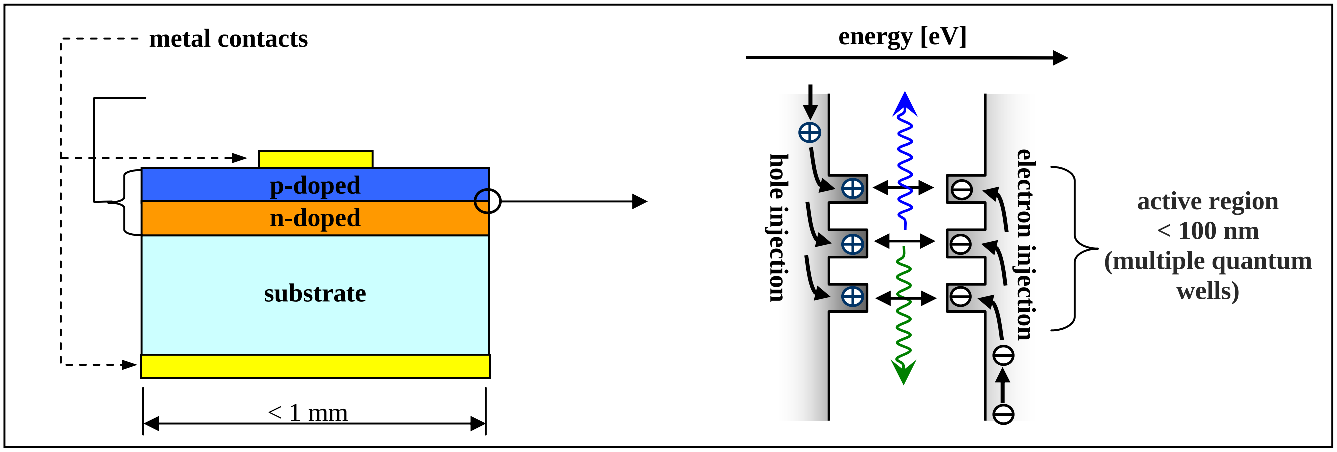

Figure 1: LED-functional principle: schematic cross view (left) and energy band diagram (right)

LED PROCESS CHAIN

1) The process chain of LED can be devided in three main parts: epitaxy, chip- and package technology (see figure 2). In a fisrt step the compound semiconductor layers are grown by use of MOCVD (Metal Organic Vapor Phase Epitaxy). The initial materials are liquid metal organyles containing Al, Ga, In and Mg which are transported by carrier gases and gases containing N, P, Si and Te. The gases are mixed and transported into the process chamber onto the substrates, which are heated up to temperatures around 1000°C. At these high temperatures, the molecules are cracked and the single atoms build the crystalline compound semiconductor layer. The state of the art substrates are sapphire and SiC for GaN-based and GaAs for AlInGaP-based LED (diameter 50 – 100 mm, thickness < 1 mm). The material quality and the design of the epitaxial layers is crucial for the internal quantum efficiency. In the blue and red wavelength range record values exceed 80% whereas in the green-yellow range the efficiencies are still below 30%.

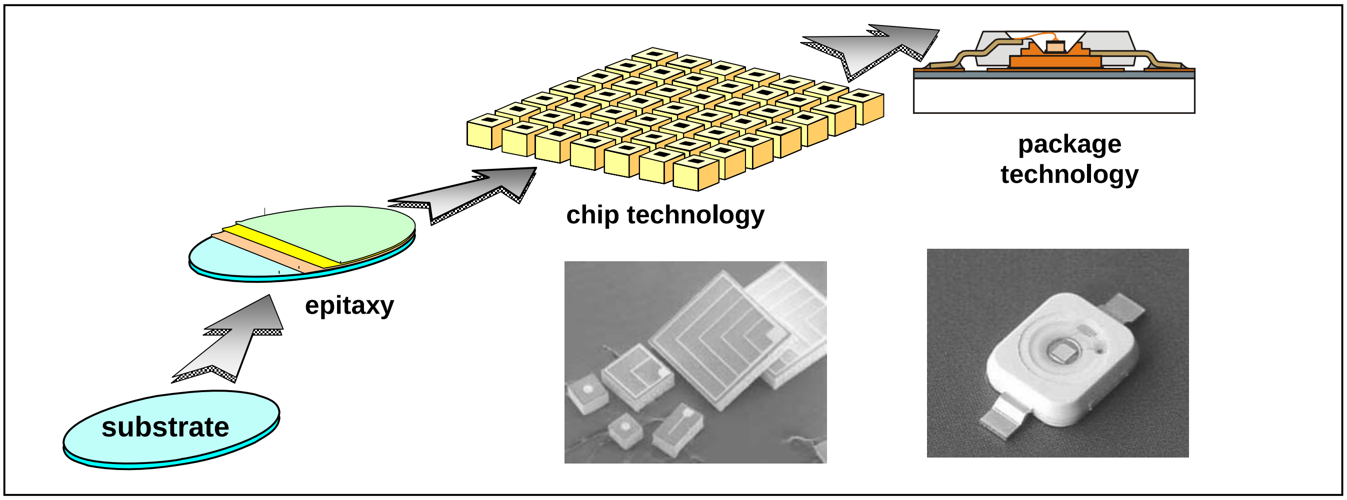

Figure 2: LED process chain

2) The goal of the second process chain part – the chip technology - is the transformation of the wafers (substrate with epitaxial layers) into single LED-chips. The focus of the chip design is to realize an optimized electrical and light outcoupling efficiency. To reduce electrical losses, the metal-semiconductor-contacts have to be optimized as well as the series resistances in current spreading layers. On the other hand, the generated photons within the quantum wells should be able to escape from the chip. Therefore, the chip design has to be optimized by reducing all kind of absorption areas like non-reflecting metal layers and by performing special out coupling structures and mirror-like metallizations. At OSRAM Opto Semiconductors, the so called Thin film technology is applied where the outcoupling efficiencies for blue emitting LED-chips exceeds 75%. The process chain regarding the chip technology includes roughly 100 single process steps in the fields of wet chemistry, lithography, deposition of metallization and dielectric layers, thermal treatments, dry etching, wafer bonding, thinning and laser dicing for chip separation. One wafer with a diameter of 100 mm contains around 7500 $1mm^2$ chips or 120000 small chips (0,25 mm x 0,25 mm).

3) The single LED-chips have to be mounted into a package for the further use in application systems. Therefore the chips are bonded into a package by gluing or metallic bonding. The package material is a combination of metal contacts and submounts (leadframe) which are embedded either in plastic or ceramics. The electrical connection to the chips is realized by the conducting bond connection of the chip backside and by the second step wire bonding, where a thin gold wire is mounted from the front chip metal contact to the second metal contact of the package. In a third step the package cavity including the bonded chip and the wire is filled with transparent cast material like epoxy or silicone. The goal of the package design is to ensure an excellent heat dissipation as well as a high outcoupling efficiency. The extraction efficiency of packages with high reflecting materials can exceed 95%.

THE COLOUR OF LED

As mentioned before, the LED technology is able to realize any colors in the visible range by choosing the right material composition in the active region of the pn-junction. By combining blue, green and red LED devices in a so called Multiled it is possible to realize any color including white when the light source is directly regarded by the human eyes or indirect by reflection on white surfaces. Therefore, Multiled solutions are applicable for projection and displays. Regarding the illumination, Multiled solutions have a small color rendering index, which means that the real colors of illuminated objects cannot be seen by human eyes since the wavelength spectrum is not continuous. A common way to realize white LED-light for illumination is to use a blue emitting chip in combination with phosphors for color conversion. Therefore phosphor particles (like YAG:Ce) which absorb blue light and emit in broad wavelength range from green to red with a maximum in yellow are mixed into the package cast material. The special design of the phosphor materials enables a wide range of emission characteristics and therefore all kind of white color temperatures (warm and cold white).

LED-PERFORMANCE

The two main measures regarding the LED-perfomance are the wall plug efficiency which is the total optical output power divided by the total electrical input power and the efficacy in lm/W, which is the brightness per electrical input power taking into account the human eye response. The wall plug efficiency is mainly used to characterize single color LED devices. The current best values at OSRAM-Opto Semiconductors are around 60% for a blue emitting device at a current density of 50 A/cm^2 and an emission wavelength of 440 nm. At lower current densities around 5 A/cm^2 the same device shows a WPE of around 75 %. By using such blue emitting chips in combination with color conversion for white LEDs, efficacies of 100 to 140 lm/W can be achieved strongly dependent on the specific color coordinates (cold or warm white, above or below Planck´s curve), the operation current and temperature. Next to the optimization of the power consumption per light output there is a variety of other characteristics that have to be fulfilled depending on the special application (color rendering index, homogeneity of color coordinates versus viewing angle and lifetime, far field pattern, lumen package per device,…).

APPLICATIONS

The applications for high brightness LED can be divided roughly in the three segments: automotive, consumer and solid state lighting. In the automotive market, LEDs are already used since decades: first for dashboard illumination, followed by rear break signals and blinkers and since a few years increasingly for full headlamp LED solutions. The typical number of LEDs in current cars is around 200 and will further increase by the transition to full LED solutions.

Examples for the consumer market are mobile phones, where LEDs are used for key-pad and display illumination as well as for flash and mini-projection. LED-TV, projection and large area displays are also a huge market driver for LEDs. The huge application area solid state lighting includes signal lighting, architectural lighting, indoor and outdoor illumination. The market is increasing drastically by the penetration of LED solutions to replace conventional light sources like incandescent and halogen lamps as well as fluorescent lamps. One prominent example is street lighting, where it is possible to realize LED solutions with better illumination homogeneity and better contrast at half of energy consumption compared to the yellowish sodium discharge lamps.

KEY CHALLENGES FOR LED-MANUFACTORING

The key challenges for LED-manufactoring are to further increase the device efficiency and to lower the costs for production. For increasing the device efficiency the key topics are the internal quantum efficiency by improvements in epitaxial layer quality and design, the light outcoupling and electrical efficiency by optimization of the chip design (outcoupling structures, reducing absorbing areas, reduction of contact and series resistance) and the package optimization regarding heat dissipation, outcoupling and conversion efficiency. For a low cost production the goal is to grow fast in capacity combined with the transition to fully automated high volume production lines. Some of the challenges here are the up scaling of the wafer diameters from 2 to 4 inch (and further), fully automated processes and process tools (automatic wafer handling) as well as automatic test and inspection systems and data coupling to reach full traceability and automatic control regarding the whole process chain. LED-production lines can benefit from the achievements made in mainstream silicon high volume production, but the wafer materials and characteristics as well the needed processes are quite different to Si-mainstream in some process sequences.

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