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THE SEMICONDUCTOR HETEROSTRUCTURES IN LEDS (LIGHT-EMITTING DIODES) – SPACE APPLICATIONS

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Abstract: *Nowadays, light-emitting diodes (LEDs) attract a lot of attention as devices for a variety of optoelectronic applications. In this paper we will briefly present their history, principles of operation, materials for their manufacture and applications. The emphasis is on the use of LED semiconductor heterostructure materials and space applications of LEDs.*

ПОЛУПРОВОДНИКОВИТЕ ХЕТЕРОСТРУКТУРИ В СВЕТОДИОДИТЕ – КОСМИЧЕСКИ ПРИЛОЖЕНИЯ

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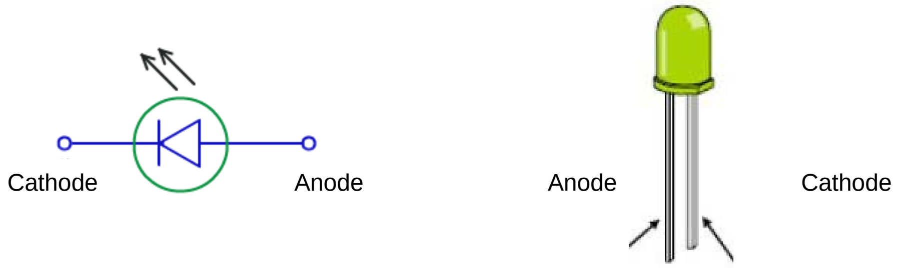
Ключови думи: *Светодиоди, неорганични полупроводникови наноструктури, полупроводникови хетероструктури, приборни приложения, космически приложения*

Резюме: *В днешно време светодиодите (LED) са обект на голямо внимание като устройства за разнообразни оптоелектронни приложения. В тази статия ще представим накратко историята им, основните принципи на действие, материалите, от които се произвеждат и приложенията им. Акцентът е върху използваните за светодиоди полупроводникови хетероструктурни материали и космическите приложения на светодиодите.*

Introduction

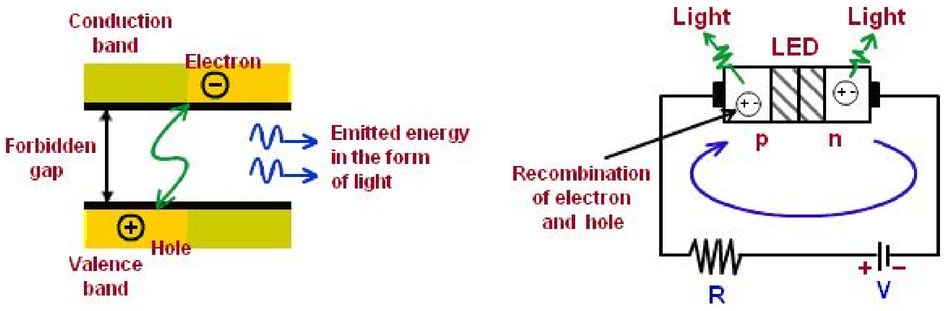
The present work is motivated by the tremendous interest in semiconductor heterostructures/nanostructures and their applications in various electro-optical devices. Semiconductor based light emission devices are an increasingly important part of modern technology. Two important light emitting devices are the light-emitting diodes (light-emission diodes, LEDs) and its companions, the laser diodes. LED and laser diode belong to the luminescent photonic semiconductor device group. Today they attract a lot of attention as devices for various optoelectronic applications [1]. An evidence are the Nobel prizes in physics of year 2000 ("for developing semiconductor heterostructures used in high-speed and opto-electronics" to Zhores Alferov and Herbert Kroemer) [2] and of year 2014 ("for the invention of efficient blue light-emitting diodes which has enabled bright and energy-saving white light sources" to Isamu Akasaki, Hiroshi Amano and Shuji Nakamura) [3]. In this paper we present briefly the LEDs' history and principles of operation; materials for their manufacture and device applications. The focus of this presentation is on the LEDs' semiconductor heterostructures and some of the space applications of LEDs.

The definition of a LED is: a semiconductor diode/device (an electronic component) that emits light when a forward voltage is applied to it or in other words, when an electric current passes through it. A LED produces artificial light (emits photons) of a single colour by recombining holes and electrons in a semiconductor. The output from a modern LED can range from visible and ultraviolet (UV) to infrared wavelengths with a very high brightness. In Fig. 1 are illustrated both the symbol (a) and the real (b) images of a LED device.



(a) **(b)**

Fig. 1. Schematic electronic circuit symbol of a LED (a) and a real image of LED as physical appearance (b)



(a) (b)

Fig. 2. The basic operation principles of the process in a LED –electroluminescence (a) and LED forward biased (b), according to [4]

Brief LED history

Since the invention of the incandescent electric light bulb by Thomas Edison in 1879, there has been a great striving for less expensive, more reliable and brighter lighting sources. Massive industries have been created to produce filament and fluorescent lamps for interior applications, sodium-discharge lamps for streets, and neon signs for ever-popular exterior advertising. The most up to date revolutionary lighting is the LED.

The emission of light from a solid material, caused by an electrical power source, was reported in the beginning of the 20th century. It was a phenomenon known as electroluminescence (see Fig. 2(a)). At that time, the materials science was not developed enough, the material properties were poorly controlled, and the emission process was not well understood. The first known report of a light-emitting solid-state diode was done in 1907 by the british experimenter Henry Joseph Round at Marconi’s Laboratories. Round reported [5] that a yellow light was produced when a current was passed through a silicon carbide (SiC) detector (the first observation of the electroluminescence). The second reported observation of electroluminescence did not occur until 1923, when the Russian Oleg Vladimirovich Lossev from the Nijni-Novgorod Radio Laboratory in Russia independently observed light emission from carborundum point-contact junctions, namely the first LED [6]. In 1955, Rubin Braunstein of the Radio Corporation of America reported on infrared emission from gallium arsenide (GaAs) and other semiconductor alloys. Other experimenters at Texas Instruments, Bob Biard and Gary Pittman, found in 1961, that GaAs gave off infrared radiation when electric current was applied. They received the patent for the infrared LED. In 1962, Nick Holonyak Jr., of the General Electric Company and later with the University of Illinois at Urbana-Champaign, developed the first practical visible spectrum LED. It was red LED with bright enough emission to use as indicator, etc. In 1972, M. George Craford, Holonyak's former graduate student, invented the first yellow LED and ten times brighter red and red-orange LEDs. In 1993 were obtained the first high brightness blue LEDs which opened the way for developing white LEDs. Shuji Nakamura of Nichia Corporation of Japan invented and demonstrated it, which was based on InGaN [7].

The electroluminescence was mostly a scientific curiosity until the invention and perfection of thin film deposition epitaxial growth techniques. Excellent quality crystal interfaces and crystal compound semiconductor layers, and heterostructures, the ability to perfect control of the doping of semiconductors, which could be tailored for specific applications, are grown by some of the following methods: MBE (Molecular Beam Epitaxy), MOCVD or MOVPE: (Metal-Organic Chemical Vapor Deposition), or (Metal-Organic Vapor Phase Epitaxy), LPE (Liquid Phase Epitaxy), etc. The historical development of blue, green, red and white LEDs is summarized in the picture below (Fig. 3).

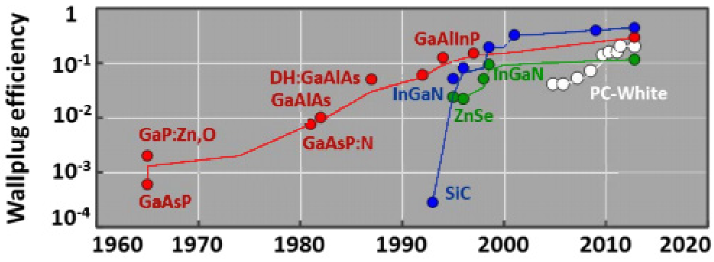


Fig. 3. Historical evolution of the performance (lm/W) for commercial red, green, blue and phosphor-converted white LEDs (according to [8])

Functioning of a LED

In order to explain the theory and the underlying principles behind the functioning of a LED, we must review and remind the physics of semiconductors. Heterojunction is called the contact of two chemically different semiconductors (of course, they are with different band gaps, lattice constants and other parameters). Heterostructure is a semiconductor structure with several heterojunctions (The heterostructures based on compounds A and B - A / B, compounds A and B are called heteropair.)

There are two basic types of LEDs: simple p-n-junction LED (homojunction or regular) and more efficient heterojunction LED (see Fig. 4 [9]). A regular LED is essentially a p-n junction diode (see Fig. 2.). When carriers are injected across a forward-biased junction, it emits monochromatic incoherent light. A LED consists of two elements of processed material called p-type semiconductors and n-type semiconductors. These two elements are placed in direct contact, forming a region called the p-n junction. The LED has a transparent package, allowing visible energy to pass through. Also, the LED has a large p-n junction area whose shape is tailored to the application. The holes are presented in the valence band and the free electrons are in the conduction band. When a p-n junction is forward biased, the electron from n-type semiconductor material crosses the p-n junction and combines with the holes in the p-type semiconductor material. Thus with respect to the holes, the free electrons are at higher energy level. When a free electron recombines with hole, the energy level related with it changes from higher value to the lower value and it falls from the conduction band to the valance band. There is an energy release due to the electron travel. In normal diodes, this energy released is in the form of the heat. But in LED the energy release is in the form of photons which emit the light energy. The entire process is called electroluminescence (Fig. 2(a)) and the diodes are called the LED.

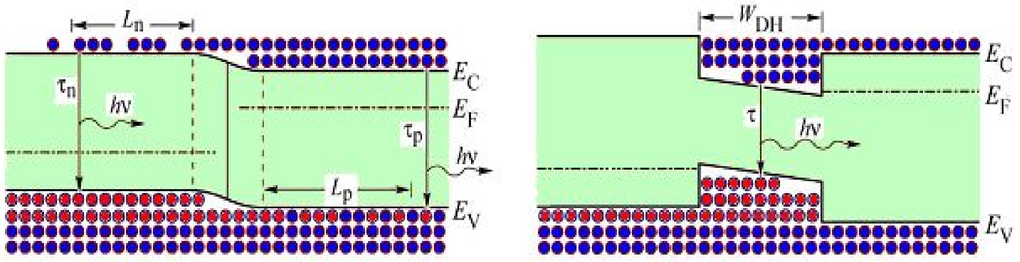
It would be very difficult today to imagine solid state physics without semiconductor heterostructures. Semiconductor heterostructures and especially double heterostructures (DHs), including quantum wells [2,3] are today the fundamental of the most advanced and perfect LEDs. There are two main problems in homojunction LEDs:

1) The quality of the semiconductor surface, where the photons emission takes place is usually poor;
2) The effective volume from which photons are emerging is quite large, because of the large diffusion distance before electron recombines with hole.

Some of the advantages of heterojunction LEDs are:

1) The active region has much more better surface conditions;
2) The emitted photons have not been absorbed in the top or bottom region.

Today, the highest efficiency LEDs [8] use the double heterostructure (DH) design (usually with a quantum well (WQ)), where the carriers are confined to the active region, W_{DH}. τ is the spontaneous recombination lifetime. Typically, for a DH, $W_{DH} > 50$ nm, while for a QW $W_{DH} = 5 \div 20$ nm. One can determine the wavelength of the light emitted from the LED, since it depends (not only) on the forbidden energy gap of the materials. Hence, the wavelength determines the colour and visibility of the light. The colour, respectively the wavelength of the emitted light, can be controlled by varying the composition and structure of semiconductor materials or/and by doping the semiconductor materials with various impurities in different concentrations. The frequency response of an LED depends on such factors as doping level in the active region; injected carrier lifetime in the recombination region; parasitic capacitance of the LED, etc.

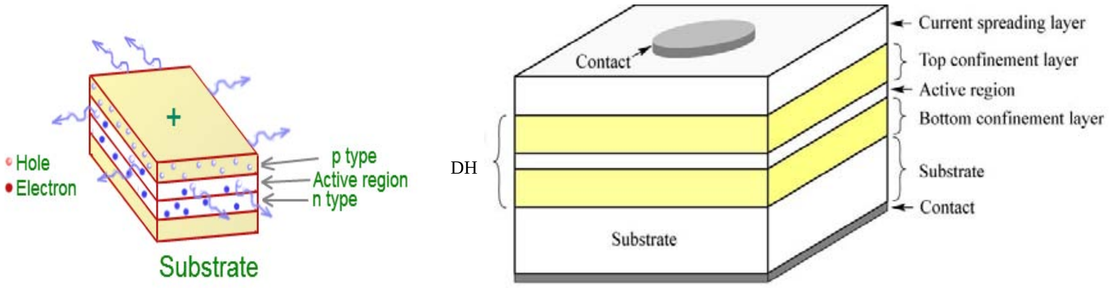


(a)   (b)

Fig. 4. Schematic representation of homojunction (a) and heterojunction (b) under forward bias [9]

Structure of LED, materials and colours

One of the methods used for LED construction is to deposit three semiconductor layers on the substrate, as given in Fig. 5.



(a)   (b)

Fig. 5. Illustration of LED structures, according to [10]

In Fig. 6 is illustrated schematically the famous Nobel blue AlGaN diode [3].

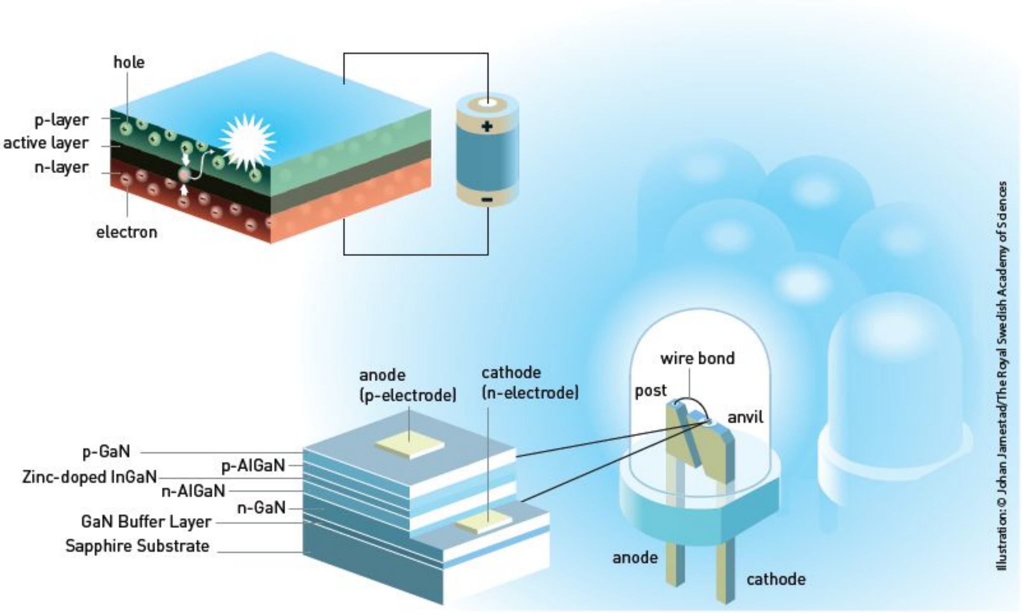


Fig. 6. Blue diode, according to [3]

Between p-type and n-type layers, there exists an active region. This active region emits light, when an electron and a hole recombine. When the diode is forward biased, holes from p type and electrons from n type, both get driven into the active region. Typical AlGaAs/GaAs DH LED structure consist of p-AlGaAs (barrier), GaAs (LED active region) and n-AlGaAs (barrier).

Most of the LED materials for light sources contain III-V ternary and quaternary compounds. In $Ga_{1-x}Al_xAs$ by varying the quantity of x it is possible to control the band-gap energy and thereby the emission wavelength over the range of 800 nm to 900 nm. The spectral width is around 20 to 40 nm.

In $In_{1-x}Ga_xAs_yP_{1-y}$ by changing $0<x<0.47$; y is approximately 2.2x, the emission wavelength can be controlled over the range of 920 nm to 1600 nm. The spectral width varies from 70 nm to 180 nm when the wavelength changes from 1300 nm to 1600 nm. These materials are lattice matched.

If the LED uses mixtures of gallium (Ga), arsenic (As) and phosphorous (P), the colour of the LED, respectively the wavelength, depends on forbidden energy gap. Hence different mixtures give the different colours. For example: the mixture of gallium phosphide (GaP) will produce the red or green colour light; the mixture of gallium, arsenide and phosphide (GaAsP) will produce the yellow and red colour light; the mixture of gallium arsenide (GaAs) will produce infrared light.

GaN materials: we can mix GaN, which emits in the UV, with InN, which emits in the red, to form InGaAs, which emits any colour from UV to red, depending on the ratio of In to Ga.

Although highly efficient coloured light sources are well applicable, but the actual need is for finding of efficient white light, necessary to illuminate homes, businesses, industry etc. There are two main ways of generating white light with LEDs. The Colour Mixing (CM) system uses three LEDs (one red, one green and one blue) in a common packing –. Phosphor-Coated (PC) system uses a blue LED to excite a phosphor much as a Hg discharge does in a traditional fluorescent lamp. Colour of white LEDs: in both CM and PC systems, the colour can be changed by altering RGB ratios or the nature of the phosphor to obtain warm white, daylight etc. In both CM and PC systems not all wavelengths are presented, so strange colour matching may result and appearances are not constant.

Table 1. LED materials and colours, according to [11]

Color	Wavelength [nm]	Voltage drop [ΔV]	Semiconductor material
Infrared	$\lambda > 760$	$\Delta V < 1.63$	GaAs AlGaAs
Red	$610 < \lambda < 760$	$1.63 < \Delta V < 2.03$	AlGaAs GaAsP AlGaInP GaP
Orange	$590 < \lambda < 610$	$2.03 < \Delta V < 2.10$	GaAsP AlGaInP GaP
Yellow	$570 < \lambda < 590$	$2.10 < \Delta V < 2.18$	GaAsP AlGaInP GaP
Green	$500 < \lambda < 570$	1.9[67] < ΔV < 4.0	GaP AlGaInP AlGaP Pure green: InGaN GaN
Blue	$450 < \lambda < 500$	$2.48 < \Delta V < 3.7$	ZnSe InGaN SiC as substrate Si as substrate—under development
Violet	$400 < \lambda < 450$	$2.76 < \Delta V < 4.0$	InGaN
Purple	Multiple types	$2.48 < \Delta V < 3.7$	Dual blue/red LEDs, blue with red phosphor, or white with purple plastic
Ultraviolet	$\lambda < 400$	$3.1 < \Delta V < 4.4$	Diamond (235 nm) BN(215 nm) AlN (210 nm) AlGaN AlGaInN—down to 210 nm
Pink	Multiple types	ΔV ~ 3.3[73]	Blue with one or two phosphor layers: yellow with red, orange or pink phosphor added afterwards, or white phosphors with pink pigment or dye over top.
White	Broad spectrum	$\Delta V = 3.5$	Blue/UV diode with yellow phosphor

Conventional LEDs are made from a variety of inorganic semiconductor materials. In the Table 1 is shown the connection of available LED colours with wavelength range, voltage drop and materials.

LED applications

LED posses very attractive features: low processing voltage, long-life with high reliability, environment-friendly light source, etc. LEDs used for lighting are high-quality LEDs with very long lifetime (100 000 hours), they are getting cheaper, and the market is currently exploding. Replacing light bulbs and fluorescent tubes with LEDs will lead to a drastic reduction of electricity requirements for lighting. Luminous efficacy is the amount of light you get for every Watt of power used. Lamp development is largely driven by seeking the highest luminous efficacy. Theoretical maximum for the ‘perfect’ lamp is 680 lm/W. Department of energy (USA) predicts increasing efficacy and has set a target of 266 lm/W for the LED package in the 2025 year. If all the lights in the world were LEDs with 200 lm/W luminous efficacy, there would be a saving of 40% of the world’s generating capacity. So the benefits of the LED lightning are energy, financial, environmental and economic. This is illustrated in Figs. 7 and 8.

3 lumens/Watt 15 lumens/Watt 70 lumens/Watt

Fig. 7. Luminous efficacy of the corresponding lamps is given below each of the pictures

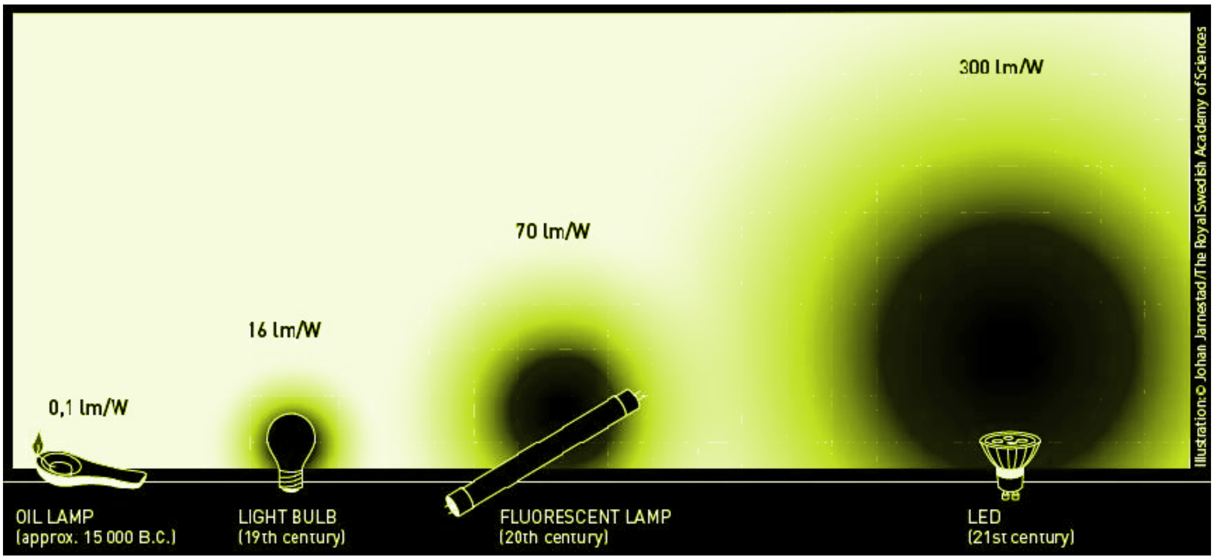


Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences

Fig. 8. LED lamps require less power to emit light than the older light sources. Efficiency is denoted in luminous flux (measured in lumen) per unit added power (measured in watt). As about one fourth of world electricity consumption is used for lighting purposes, the highly energy-efficient LED lamps contribute to saving the Earth’s resources, according to [3]

LEDs are the most common light source in all of the electronic equipment. For example, they are widely used in devices for displaying the time or other types of data on screens. In 1968, the first commercial use of mass-produced LEDs was in Hewlett Packard calculators. In 1989, appeared the first LED traffic lights. And now they are everywhere. In 2001, the first LED pocket torches: these were the first uses for white LEDs. The brightness of LEDs doubles every 3 years.

The first decade of the 21st century saw high power LEDs developed and to date the trend has continued, though heat sinking is a major problem. High power LED’s are now found in many applications like LED TV’s, theatre lighting, projector lamps and general and point lighting in the home.

For photonic communications, requiring data rate 100-200 Mb/s with multimode fiber with tens of microwatts, LEDs are usually the best choice. Device LED configurations used in photonic communications are: surface emitters (front emitters) and edge emitters.

Today, GaN-based LEDs provide the dominant technology for back-illuminated liquid crystal displays in many mobile phones, tablets, laptops, computer monitors, TV screens, etc. Blue and UV-emitting GaN diode lasers are also used in high-density DVDs, which has advanced the technology for storing music, pictures and movies. Future application may include the use of UV-emitting AlGaN/GaN LEDs for water purification, as UV light destroys the DNA of bacteria, viruses and microorganisms. In countries with insufficient or non-existent electricity grids, the electricity from solar panels stored in batteries during daylight, powers white LEDs at night. There, we witness a direct transition from kerosene lamps to white LEDs [8].

The use of LED devices for illumination inside space cabin and outside have been well exploited in the past few years; these include, for, the in-cabin application on the bio-science satellite in 2007 and the out-of cabin application on spacecraft in 2008 to shine on the first step in space of Chinese astronaut [12]. The low voltage operation of LEDs is a very desirable feature for the illumination tools of astronauts. Also, due to the direct matching between solar cell voltage and the operation voltage of LED illumination, the latter will be the best method in space stations for illumination and photo synthesis processes. Production of all items used for space application characteristically involve high cost, have high technical risk, require long lifetime and self maintenance and require high probability of success. Hence it is very interesting to study the LED property in the context of space application, since there is still lack of data on the application of LEDs in space. A new field of study will be opened on the study of failure probability, the strategy to avoid the failure, and the reliability of LED device in the illumination-lamp for space application. It is very important to precisely estimate the lifetime of the LED lamp to make sure that the LED device is only used in its stable lifetime period. The most efficient way is to eliminate device failures beforehand (according to [12])]. Up to now there is still a lack of the high quality and high power LED for illumination application in space. It is necessary to systematically study the criterion for the LED device selection for eliminating device failure beforehand. Among the various factors leading to device failure, the temperature of the active layer is one of the key parameters to determine the lifetime of LEDs. The reason is that the activation energy of the defects in GaN based LEDs, depends on the temperature.

In Figs. 9 and 10 (following [12]) we can see the successful space application of LED lamps. The yellow arrow in Fig. 9 indicates the LED lamp in the space near by the spacecraft. The light shining on the spacecraft is from the LED lamp.

Fig. 9. The status of LED white light illumination lamp applied to external cabin. The arrow indicates the LED white light illumination equipment. The flyer on the left side is shenzhou-7 spaceship

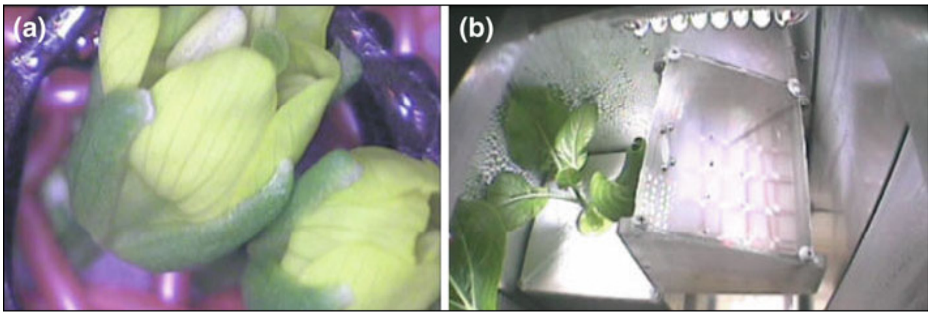


Fig. 10. The photos captured on the Shi Jian-8 satellite (a) the plant grown under the illumination of LED lamp, (b) LED illumination lamp equipped in the plant growth box

In the case of Shi Jian-8 recoverable satellite of China, the LED illumination technology has provided high efficiency with high reliable white/red LED combination illumination for the photosynthesis under microgravity in satellite cabin. The green botanic photosynthesis needs enough light intensity. However, the electrical power provided in the satellite is very limited so that they choose high irradiance efficiency as the illumination source. With low-power consumption, the white light LED lamp provides reasonable illumination intensity in the illumination cycle research about the botanic growth. Also the LED lamp provides proper light intensity for microscope camera photography. The photos (Fig. 10) transmitted from satellite shows the good growth of plants in the space lighted by LED lamp illumination. From the successful application of the LED lamp in space, the authors in [12] conclude that the commercial LED chip can be used for the space application by the careful selection on their reliability. The LED lamp with lower junction temperature is preferred for the space application. It was the first time for the white light illumination by using LED lamp in space [12].

Conclusions

This brief survey of the LEDs could enhance the common understanding of some modern and contemporary knowledge and devices. Both experimental and theoretical studies of the LEDs structures are quite important for development of the new LED device applications. They could facilitate the search for new material heterostructures possessing unique electron, optical and photonic properties. This review will also help and tremendously facilitate the understanding of the importance of semiconductor quantum wells (QWs) in LED structures.

Production of all items used for space application characteristically involve high cost, have high technical risk, require long lifetime and self maintenance and require high probability of success.

As the illumination-technology by using of LED posses attractive features, such as low processing voltage and long-life with high reliability, it would be very well suited for illumination related to space-flight and satellites. The low voltage operation of LEDs is a very desirable feature for the space applications for astronauts. Also, due to the low operation voltage of LED illumination, the latter will be the best method in space stations for illumination and photo synthesis processes.

Hence it is very interesting and useful to study the heterostructure properties in the context of LED space application!

Last but not at least, our experience in the Stark effects on the electronic states in QWs [13-15] will be of great help in the future study of unknown and possible QW properties, and QW structures for new potential LED device structures, and applications.

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