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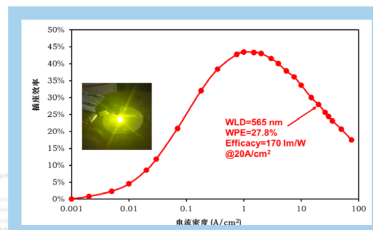
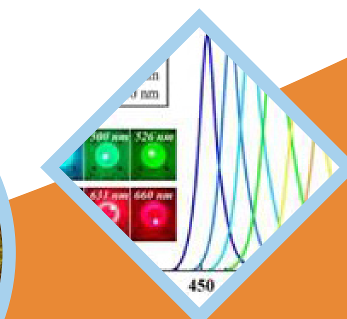
Progress of GaN-on-Si Visible Light LED and Pure LED Lighting Technology





International SSL Alliance

Address: Room1305, Block 2D, Zhongguancun IC Park, No. 9 Fenghao East Road, Haidian District, Beijing, China (100094)
Tel: 86-10-62607581
Fax: 86-10-62607258
Email: secretariat@isa-world.org
Website: www.isa-world.org

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Academician Jiang Fengyi, Nanchang University and his team: Zhang Jianli, Xu Longquan, Wang Guangxu, Ding Jie, Wang Li, Mo Chunlan, Wang Xiaolan, Zheng Changda

With almost 20 years of rapid development, LED lighting industry has entered a mature stage. But there is still broad development space in terms of technology. For a long period in the past, the development of visible light LEDs was quite uneven. GaN–based blue LEDs and GaP red LEDs have relatively high luminous efficiency, while that of the yellow and green LEDs between these two is relatively low, especially the yellow LEDs, which luminous efficiency has not reached the practical level for a long time. This phenomenon is also known as the "yellow–green gap." The lack of high–efficiency yellow LEDs makes the excitation phosphor by the blue LED become the mainstream method of white light illumination. However, in the light–to–light conversion process, phosphors have problems such as large heat loss, slow light response, and difficulty in combining light quality and luminous efficacy, which restricts the rapid development of LEDs towards the high–quality, healthy and smart lighting direction to some extent.

In addition, although GaP LEDs have been developed and become mature firstly, compared with GaN–based LEDs, there are still some shortcomings. GaP LEDs have relatively strong temperature effects and size effects, and weakness when being applied to the new display field. The band gap of the aluminum gallium indium phosphide (AlGaInP) quaternary system with GaN as the main body can be adjusted between 0.7eV and 6.2eV theoretically, which can completely cover the visible light (1.6–3.1eV) range; moreover, GaN materials also have many advantages such as high mechanical strength, stable chemical properties, high thermal conductivity, and strong radiation resistance. If the emission wavelength of GaN–based LEDs can be further extended

to the orange and red light range, then the LED with any bands in the visible light range can be made of nitride, and this is also the ultimate ideal in the field of LED luminescence.

This report mainly introduces the latest progress of GaN–on–Si visible light LEDs and visible light LED–based pure LEDs lighting technology. Through collaborative innovation of process and equipment, the GaN–on–Si technology has solved the high–efficiency yellow LED shortage problem in the world for a long time. Accordingly, the luminous efficiency of the green LEDs between the yellow and blue ones has also been significantly improved. Meanwhile, the violet and cyan LEDs close to the blue band have been slightly optimized in terms of the blue LED structure and process, achieving relatively high luminous efficiency as well. By improving the yellow LED quantum well indium (In) composition and quality, at low current densities, the GaN–on–Si red–orange LEDs have also achieved relatively high luminous efficiency. So far, the GaN–on–Si LEDs have completed the coverage of the visible spectrum, and the red, orange, yellow, green, cyan, blue, and violet seven–color LEDs have achieved high–efficiency luminescence (some bands are realized at low current densities). And pure LED lighting based on phosphor–free multi–primary color LEDs has also been successfully realized.

1. Key GaN-on-Si technologies

GaN–on–Si technology is a systematic project and has formed a complete ecosystem presently. Comparing it to a tree: with lots of cell technologies as fine roots, the four roots of material growth, chip technology, device physics and equipment development are constituted, and then the trunk of GaN–on–Si technology is formed, which grows branches such as light–emitting diodes, lasers, power electronic devices, detectors, and photovoltaics, and finally many fruits in lighting, display, backlight, indication, agriculture, medical treatment and other application fields are born. The GaN–on–Si material growth, chip technology, device physics and equipment development will be introduced below.

1.1 Three mismatches and GaN material growth

It has always been the dream of the academia and the industry to prepare the third–generation semiconductor

GaN luminescent materials and chips on the first–generation semiconductor material silicon. However, there are great difficulties and challenges. A group of large international companies including IBM, Bridgelux in the United States, Osram in Germany, Plessy in the United Kingdom, Toshiba in Japan, and Samsung and LG in South Korea have successively carried out research on GaN–on–Si LEDs, but failed to launch products successfully.

The main difficulties of GaN–on–Si LED material technology can be attributed to three mismatches: thermal mismatch, lattice mismatch and band gap mismatch, which are caused by the difference in coefficient of thermal expansion, lattice constant, and band gap between the GaN epitaxial material and the substrate material silicon respectively. As shown in Table 1, firstly, the coefficient of thermal expansion of the silicon substrate was much smaller than GaN. When GaN was grown at high temperature (~1,000 C) and then cooled to room temperature, the silicon substrate produced a huge tensile stress on the GaN epitaxial film, causing cracks in the GaN material, making it impossible to manufacture devices; secondly, there was a huge difference in lattice constants between GaN and silicon substrates, resulting in excessively high dislocation density in GaN materials, thereby leading to low quantum efficiency; thirdly, the band gap of the silicon substrate was only 1.12eV, which was much smaller than GaN and visible light InGaN quantum well. The light emitted by the quantum wells would be absorbed by the silicon substrates, resulting in low luminous efficiency.

Table 1 Difference in coefficient of thermal expansion, lattice constant, and band gap between GaN and silicon

Material	Coefficient of thermal expansion	Lattice constant	Band gap
GaN	$5.6*10^{-6}$ K^{-1}	a=0.3189 nm	3.40 eV
Silicon	$2.6*10^{-6}$ K^{-1}	a=0.3840 nm	1.12 eV

Grid substrate technology has been developed to solve the problem of cracks caused by thermal mismatch. As shown in Figure 1, with the application of the mask technology, the substrate was separated into independent cells with the same size as the chip, and GaN was grown in independent cells. Through breaking the whole into parts, the stress concentration effect of the whole piece of GaN–on–Si materials was eliminated, making the chip working area crack–free, and solving the problem that the chip cannot be manufactured due to material cracks. In addition, there is also a common method that uses AlGaN with a graded composition as a buffer layer, and uses the lattice distortion between different composition AlGaN layers to accumulate compressive stress to balance the tensile stress caused by thermal mismatch, which can also solve the crack problem of GaN–on–Si. Compared with the AlGaN graded buffer layer technology, the advantage of the grid substrate technology is that when the quantum well is grown, part of the tensile stress of the epitaxial layer of the silicon substrate is retained; while eliminating cracks, the tensile stress of the substrate is used to improve the incorporation ability of indium in the InGaN quantum well and the material quality, which is also an important factor for the success of the GaN–on–Si LEDs in the long–wavelength band.

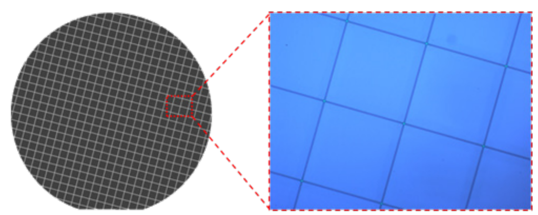

Figure 1 Schematic diagram of GaN/Si-based LED epitaxial material gridding selective area growth method

The GaN material was directly grown on the silicon substrate, and the dislocation density exceeded 1010 cm−2, making it difficult to obtain devices with high luminous efficiency. An integrated transition layer technology has been developed to reduce the high dislocation density caused by lattice mismatch. Firstly, a layer of aluminum nitride (AIN) was grown on a silicon substrate, and then the lattice mismatch between GaN and AIN was used to grow 3D island–shaped GaN on AIN; and then the 3D GaN was merged with lateral epitaxy, and the dislocation density was adjusted to 5*108 cm−2; At the same time, dislocations were used to generate V–pits in the quantum well to form a 3D pn junction to improve the LED luminous efficiency.

Solving the problems of cracks and high dislocation density is the fundamental work for the growth of GaN–on–Si materials. Besides, lots of cell technologies have been developed in terms of the growth of GaN–on–Si LED materials, such as stress preparation layer technology, and V–pit technology, which have been reported before and will not be repeated here.

1.2 Film transfer and vertical structure LED chips

Thin film transfer technology has been

developed on the chip side to solve the light absorption in the substrate caused by band gap mismatch. The GaN epitaxial film was bonded to a new substrate with a reflector, and the original silicon substrate was selectively etched away, being made into a thin–film LED chip with a vertical structure. The specific process flow is: First, evaporate an Ag reflector layer on the surface of the p–GaN on which the LED structure is grown; then bond it with another conductive Si substrate through metal thermal bonding; and then peel off the original Si substrate through wet etching to expose the surface of n–GaN; and then roughen the n–GaN surface by wet etching; finally, evaporate n–electrodes on the n–GaN surface to fabricate vertical structured, thin–film GaN–based LED chips with reflector and roughened surface, as shown in Figure 2(a).

Presently, there are three common chip structures for GaN–based LEDs, which are vertical structure, horizontal structure, and flip–chip structure respectively. The substrate difference has caused the difference of chip structures. The sapphire LEDs are mostly of horizontal structure, as shown in Figure 1(b). Since it is difficult to peel off the sapphire substrate, GaN should be etched to the n layer to make the n electrode and the p electrode are located on the same side, while the reflector is on the back of the sapphire. The manufacturing process of chips with this structure is simple, but due to the great difference in current paths between different light–emitting positions, there is a problem of current congestion; moreover, sapphire has low thermal conductivity and poor heat dissipation. Therefore, it is difficult for LEDs with a horizontal structure to work at high current densities. In order to improve

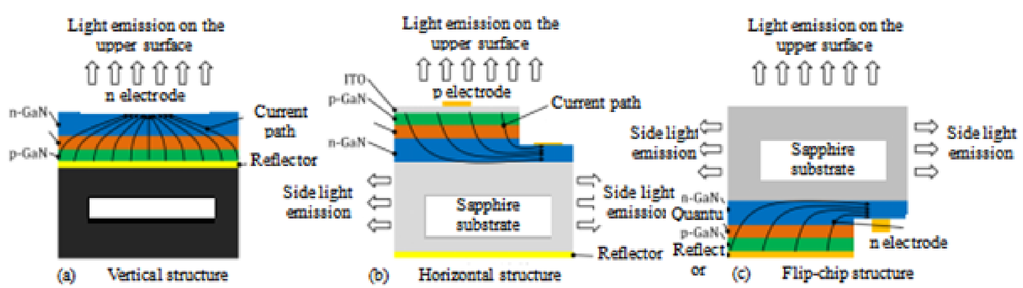

Figure 2 Comparison of light emission and current spreading methods GaN-based LED with (a) vertical structure, (b) horizontal structure, and (c) flip-chip structure

the heat dissipation performance, the LED can be turned upside down. As shown in Figure 2(b), the heat is directly conducted from the p electrode and the n electrode, which increases the working current density of the LED, but the problem of current spreading still exists. The current distribution of LED chips with a vertical structure is more even; meanwhile, the heat dissipation performance of the silicon substrate is good, which can still show good performance and reliability under high current working conditions. For LED chips with horizontal structures and flip–chip structures, since the sapphire is thick (50–80μm) and transparent, with 5 light–emitting surfaces, the consistency of color temperature, color rendering, brightness, etc. for the white light illumination space is not ideal. Moreover, since the light cannot be focused, the range is short. The silicon–based LEDs with the vertical structure have very thin epitaxial films (2–3μm), which are approximate to single–sided light emission. After being packaged as white light, the light spots are good, and the color quality consistency in different directions is good. At the same time, the light can focus well with a long range. Such characteristics are suitable for application fields with strong light directionality requirements such as stage lights and glare flashlights.

1.3 V-pits and 3D pn junctions in GaN

Another important factor for the success of GaN–on–Si LEDs is the rational use of defects. The dislocation density in GaN–on–Si materials can be controlled within a reasonable range with the application of the integrated transition layer technology. If V–pits are formed in quantum wells with the use of dislocations, the LED luminous efficiency can be improved effectively.

V–pit is a common bulk defect in nitrides, and it is named after its cross–section that resembles the character "V". V–pits generally originate from dislocations and expand outward along the dislocations to form holes in the inverted hexagonal pyramid shape, as shown in Figure 3. The study found that since the thickness of the sidewall quantum well of the V–pit is relatively thin and the In composition is relatively low, it can effectively shield dislocations and reduce the probability of non–radiative recombination, thus making the nitrides maintain relatively high luminous efficiency under a high dislocation density. For long–wavelength LEDs, the low growth temperature makes the quantum well quality relatively worse. Therefore, the shielding effect of V–pits on dislocations will be more obvious; The high In composition makes the stress in the quantum well greater, and the V–pits, as a bulk defect, can greatly reduce the stress during the growth of the quantum well. Therefore, V–pits are very important for long–wavelength LEDs.

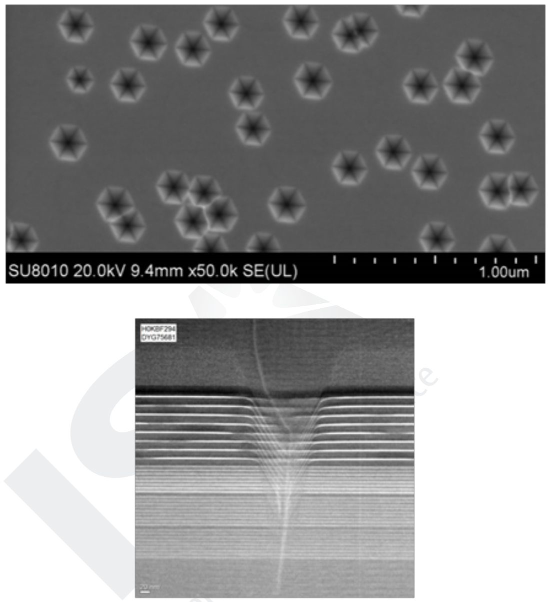

Figure 3 V-pits in GaN-on-Si material (a) SEM surface morphology (b) TEM cross-section morphology

In the process of studying the device performance, some new characteristics of the V–pits were discovered. It was observed through variable temperature electroluminescence that the sidewall quantum well of the V–pits has the electroluminescence ability, indicating the possibility of hole injection from the sidewall of the V–pits. It was found through simulated calculation that the barrier height of the holes on the sidewall of the V–pit is smaller than that of the quantum well in the direction of the platform, indicating that hole injection into the quantum well through the sidewall of the V–pits is much easier. In addition, the phenomenon of hole leakage via the V–pits to the n side was also found, indicating that the V–pits changed the recombination position of the carriers.

The idea of enhanced hole injection with a V–shaped 3D PN junction is proposed on the above basis. In traditional diodes, the interface between n–type materials and p–type materials is a plane, which can be regarded as a two–dimensional structure, and the carrier movement direction is simple, from n to p or from p to n; as shown in Figure 4, the existence of the V–pits made n–GaN and p–GaN interlace each other, forming a 3D interface, and the transport path of carriers became more complicated. No hole injection into the quantum well near the n side via the relatively thick p–AlGaN and multilayer barriers was needed, but direct injection into the quantum well via the sidewall of the V–pits, which greatly improved the hole injection efficiency, the carrier matching

degree, and the luminous efficiency. The experiment showed that the introduction of V–pits in the LED could effectively improve the In incorporation ability in the quantum well, reduce the efficiency droop, and reduce the device voltage.

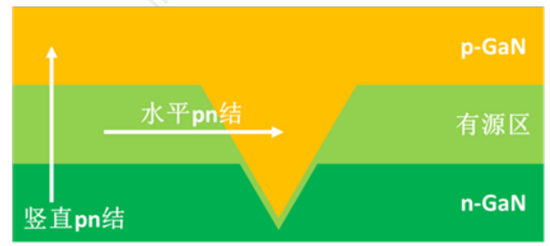

Figure 4 Schematic diagram of the 3D PN junction formed by the V-pits in the GaN-based LED

In addition to the V–pits introduction for dislocation shielding, stress reduction and hole injection improvement, by designing the density, size, sidewall composition, and sidewall thickness of the V–pits, to some extent, the carrier transport path can also be adjusted, the light–emitting position can be controlled, and the device performance can be improved.

1.4 Special MOCVD equipment for GaN-on-Si LEDs

MOCVD is the main equipment for material growth and plays a decisive role in the performance of LEDs. The current commercial MOCVD is mainly designed for blue LEDs on sapphire, which is not suitable for the growth of long–wavelength LED materials.

With respect to the growth characteristics of high In composition materials, based on the "dense coaxial coupling nozzle", special MOCVD equipment for high In composition InGaN materials has been independently developed. As a core component, the nozzle structure is shown in the figure, with the inner part of the metal organic (MO) and ammonia (NH3) upper and lower intake chambers; MO enters the reaction chamber through the small nozzle hole in the center; the NH3 pipe is sheathed outside the MO pipe, and NH3 enters the reaction chamber via the peripheral annular channel. Features of this design include: first, MO and NH3 are coupled into the reaction chamber, eliminating the adduct memory effect; second, the MO and NH3 pipelines are coaxial, ensuring a relatively good gas microhomogeneity; third, the dense intake pipes make the gas macrohomogeneity good; fourth, the memory effect is reduced with a small MO nozzle area and faster MO flow rate, and the interface is steeper; finally, the NH3 nozzle area is large, which can greatly increase the NH3 concentration and increase the incorporation ability of In.

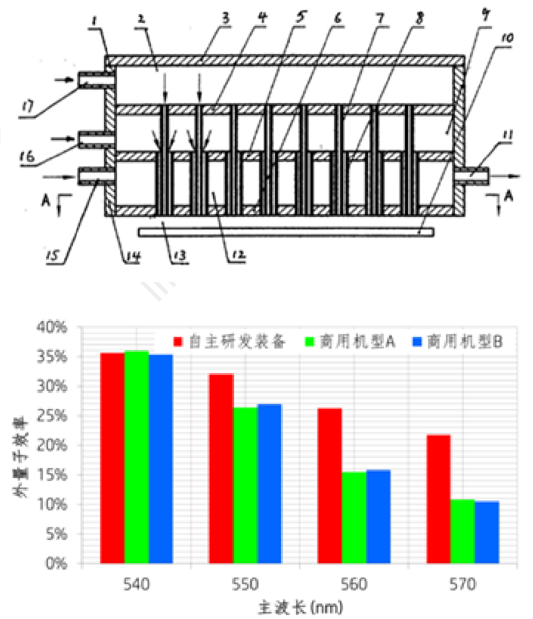

Figure 5 (a) Nozzle structure of the special MOCVD equipment for long-wavelength GaN-on-Si LEDs, (b) luminous efficiency comparison between long-wavelength LEDs grown on the independently developed special MOCVD equipment and LEDs with different bands grown on the commercial equipment

Two commercial MOCVD models were selected for controlled trials, and the same LED epitaxial structure was grown and fabricated into devices. As shown in Figure 5(b), the luminous efficiency has little difference near 540nm; however, as the wavelength increased, the LED luminous efficiency of long–wavelength LEDs grown on the independently developed special MOCVD equipment was relatively higher; the longer the wavelength, the more obvious the advantage. At 570nm, the LED luminous efficiency grown on the special MOCVD equipment for the long–wavelength LEDs was close to twice that of the commercial MOCVD.

2. GaN-on-Si Visible Light LEDs

The luminous efficiency of visible light LEDs is very unbalanced. Among them, the luminous efficiency of the green and yellow light areas where human eyes are most sensitive to light has long been far lower than that of the blue/violet light and red light. This phenomenon is called the "yellow–green gap" and causes high–efficiency white LED lighting to be realized by exciting the phosphors with blue light. Professor Holonyak, the inventor of LED that emits red light, pointed out in 2012: "LED is in its infancy in some ways. And nobody has solved the problem of getting yellow very well."

Whether it is AlGaInP or InGaN material systems, the performance in the yellow band has long been unsatisfactory. For AlGaInP materials, the luminous efficiency is very high in the red band, but as the wavelength becomes shorter to the yellow band (near 570 nm), its energy band will change from a direct band gap to an indirect one, resulting in a sharp

drop of luminous efficiency. This factor is a physical bottleneck that is difficult to overcome. For the direct band gap InGaN material system, the biggest problem is that it is difficult to grow high–quality InGaN quantum well materials, which is a technical bottleneck and is expected to break through by innovations in material structure, growth methods, process technology, equipment design, etc.

Based on mature GaN–on–Si blue LED technology, combined with the newly developed MOCVD equipment and V–pit technology, a breakthrough in InGaN yellow LEDs has been achieved, ending the long–term lack of efficient yellow LEDs. As shown in Figure 6, at a current density of 20A/cm2, the 565nm yellow LED socket efficacy reached 27.8%, which was nearly three times higher than the best international level previously (9.6%), and the corresponding luminous efficacy was 170lm/W, reaching a practical level.

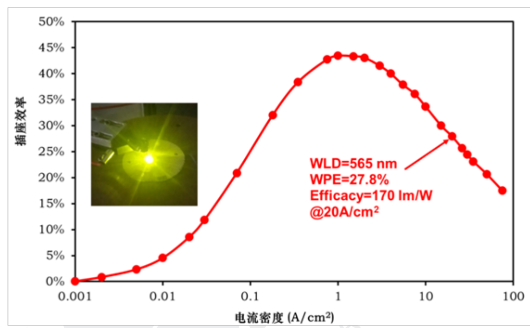

Figure 6 Curve of the GaN-on-Si yellow LED socket efficacy with current density

By adjusting the In composition in the quantum well, while optimizing the epitaxial structure and growth conditions, the emission wavelength of GaN–on–Si LEDs has completed the coverage of the visible spectrum, red, orange, yellow, green, cyan, blue, and violet seven–color LEDs all achieved high–efficiency luminescence (some bands were achieved at low current densities). Between red light and violet light, LEDs of any wavelength can be made of GaN–on–Si. Figure 7 showed the socket efficacy of GaN–on–Si LEDs with different wavelengths in the range of 400–620nm (namely, the ratio of LED output optical power to input electrical power, hereinafter referred to as luminous efficiency). At the current density of 20A/cm2 (red circle), the 399nm violet LED luminous efficiency was 71.7%, that of 450nm blue LED was 68.3%, that of 495nm cyan LED was 54.8%, that of 520nm green LED was 46.6%, that of 565nm yellow LED was 27.8%, that of 598nm orange LED was 9.5%,

It can be seen that the luminous efficiency of GaN–on–Si LEDs decreased rapidly as the wavelength increased. This phenomenon is also called the wavelength droop of the LED luminous efficiency. The luminous efficiency of GaN–on–Si LEDs was very high in the blue, cyan, and violet bands, all exceeding 50%; while the luminous efficiency was relatively high in the yellow and green bands, between 25% and 50%; and the luminous efficiency in the orange and red bands was still at a relatively low level, less than 10%. The main reason for the wavelength droop is related to In in the GaN–based LED quantum well. The longer the emission wavelength of the LEDs, the higher the In composition required in the quantum well. Correspondingly, the greater the lattice mismatch between the InGaN quantum well and the GaN barrier, the greater the compressive stress on the quantum well, at the same time, the lower the growth temperature of the quantum well, thereby reducing the quality of the quantum well, aggravating the overflow of carriers, and causing a decrease in the quantum efficacy of the LEDs. The highest luminous efficiency of the GaN–on–Si LEDs appeared near 430nm, reaching 73.2%. At that time, the In composition in the quantum well was relatively low; the compressive stress on the well was small, and the well–barrier potential difference was relatively large; the further shortening of the wavelength would reduce the restriction effect of the barrier on the carriers in the well and result in a decrease in the luminous efficiency of the LEDs.

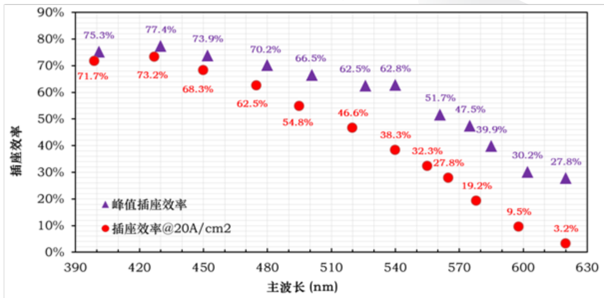

Figure 7 Luminous efficiency of GaN-on-Si visible light LEDs with different wavelengths

Peak luminous efficiency refers to the maximum luminous efficiency that a certain LED can achieve at different current densities. Under normal conditions, the luminous efficiency of LEDs increases first and then decreases as the current density increases. At low current densities, non–radiative recombination caused by defects dominates, so the luminous efficiency is low; with the saturation of defects, the LED luminous efficiency reaches its peak, so the peak luminous efficiency can reflect the quality of the LEDs´ quantum well to some extent; the further increase of the current density, auger recombination, carrier overflow, and carrier mismatch will lead to a decrease in the luminous efficiency of the LEDs. This process is also called the current Droop of LED efficiency. The current droop can be alleviated and the luminous efficiency of LEDs at high current densities can be

improved through the improvement of the epitaxial structure, but the peak luminous efficiency cannot be exceeded. Therefore, the peak luminous efficiency also represents the potential of LED luminous efficiency. The violet triangle in Figure 7 was the peak luminous efficiency of GaN–on–Si LEDs with different wavelengths, among which, that of 401nm violet light was 75.3%, that of 451nm blue light was 73.2%, and that of 480nm cyan light was 70.2%. The peak luminous efficiency all exceeded 70%, but the improvement was not significant compared with that at 20A/cm2. The main reason was the relatively low In composition of the short–wavelength quantum well, and the current droop was not obvious; in the yellow and green bands, the peak luminous efficiency of 525nm green LEDs was 62.5%, that of 540nm yellow–green LEDs was 62.8%, and that of 575nm yellow LEDs was 47.5%, significantly higher than that at 20A/cm2 and exceeding the luminous efficiency of phosphor conversion. If the luminous efficiency at high current densities is increased to the peak luminous efficiency, the luminous efficiency of pure LED lighting based on multi–primary colors will surpass that of phosphor LEDs significantly; in the orange and red light bands, the peak luminous efficiency of 602nm orange LEDs was 30.2%, and that of 620nm red LEDs was 27.8%, with a significant improvement compared with that at 20A/cm2, which can be used in applications with low current densities, such as display and instruction.

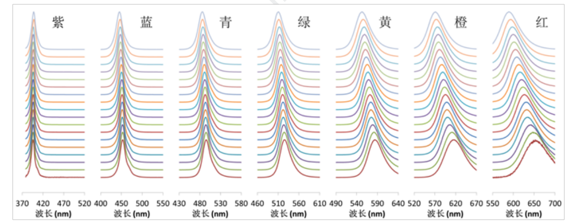

Figure 8 Luminescence spectra of GaN-on-Si seven-color LEDs at different current densities

Figure 8 showed the luminescence spectra of GaN–on–Si red, orange, yellow, green, cyan, blue, and violet seven–color LEDs at a current density of 20A/cm2. It can be observed that the spectrum of the violet LED was very narrow, with a half peak width of only 11nm and a relatively good symmetry of the spectrum. As the wavelength increased, the half peak width of the spectrum became larger in turn. The half peak widths of the spectra of blue, cyan, green, yellow, orange, and red LEDs were 15nm, 19nm, 25nm, 38nm, 45nm, and 52nm respectively; The blue shift of the peak wavelength with the increase of current density was more serious; at the same time, the symmetry of the spectrum became worse. The right side of the peak wavelength of a single spectrum was obviously wider than the left side, the reason of which was that with the increase of the wavelength, the In composition in the quantum well increased, and the uniformity of the indium composition became worse and the piezoelectric field became larger.

3. Pure LED Lighting Technology and its Application Prospects

For a long time, due to the lack of high–efficiency LEDs with some bands, using blue LEDs to excite yellow phosphors to obtain white light (hereinafter referred to as phosphor LEDs) has become the mainstream lighting solution, as shown in Figure 9(a). With simple process and low costs, this scheme has made significant contributions to energy conservation and emission reduction. However, it was not pure LED lighting, and it has not broken away from the "converted luminescence of rare earth doped phosphors " of the traditional fluorescent lamp (excited by ultraviolet light) category. The pure LED lighting technology in a real sense is to synthesize white light with LEDs of different colors directly. Compared with fluorescent LED lighting, there is no down–conversion energy loss, and the luminous efficiency potential (i.e., energy conservation potential) is greater; the coordinated development of light quality and luminous efficiency is taken into consideration; the spectrum is flexible and adjustable, suitable for smart lighting and precise lighting; the proportion of blue light is controllable, which can reduce the health risks caused by blue light and improve the safety of light (i.e., lighting); every color of light can be used as a signal channel and there is no phosphor luminescence delay, compatible with high–speed visible light communication; free from the shackles of phosphors, the rare earth strategic resources can be saved. In addition, pure LED lighting technology can also be integrated with fields such as display, communications, agriculture, and medical treatment to further promote the development of other industries. As a very important common key new technology, it is regarded as the new direction for the future development of semiconductor lighting. Since 2015, the DOE of the United States has included pure LED lighting technology in its solid–state lighting technology development roadmap. With the emergence of GaN–on–Si high–efficiency yellow and green LEDs, the white light mixed through using

multi–color LEDs (hereinafter referred to as multi–primary color LEDs) has become possible, as shown in Figure 9(b).

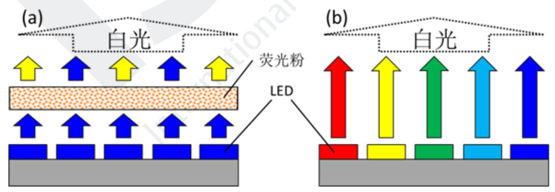

Figure 9 Schematic diagram of two implementation schemes of white LEDs: (a) Blue LED excitation phosphor mode (b) Multi-color LED mixed mode

The 2,941K warm white light was synthesized with the use of GaN–on–Si blue, cyan, green, and yellow LEDs with high luminous efficiency and commercial GaP red LEDs, with the color rendering index (Ra) reaching 97.5, and the luminous efficacy of 121.3lm/W, equivalent to the phosphor LED with the same color temperature and color rendering index.

Since the ratio of the blue light in the phosphor LED spectrum to the yellow light emitted by the phosphor was fixed, the spectrum could not be adjusted after the packaging was completed, while the multi–primary color LEDs can individually control the luminous intensity of LEDs with different colors, change the luminescence spectra, and adjust the color temperature and brightness of the LEDs. A smart lighting source was developed with the use of GaN–on–Si blue, green, and yellow LEDs and commercial GaP red LEDs, as shown in Figure 10. The color temperature of the light source could be continuously adjusted from 1,500K to 6,500K while maintaining a relatively high color rendering index (between 93–95); the luminous efficacy of the LEDs was 120–150lm/W, and the peak luminous efficacy was 190–220lm/W. If the luminous efficiency of each color LED can be increased to 86% in the future, the theoretical limit of the luminous efficacy of the multi–primary color LEDs can reach 290–340lm/W.

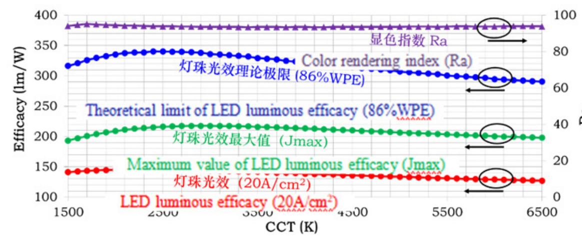

Figure 10 Curve of the changes in luminous efficacy and the color rendering index of the phosphor-free four-primary color variable color temperature LED light source along with the correlated color temperature

In recent years, the blue light hazards of LEDs have attracted much attention. Too much exposure to blue light will not only cause damage to human eyes, but also affect the body's physiological rhythm and harm health. The blue light component in the spectra of phosphor LEDs, especially those with high color temperature is extremely high; whereas, the multi–primary color LEDs can reduce the blue light hazards by adjusting the spectra. In combination with GaN–on–Si yellow LEDs and commercial GaP red LEDs, a golden LED healthy lighting source with ultra–low color temperature and without phosphor and blue light was developed, avoiding the risk of short–wavelength light hazards of blue LEDs during home lighting at night. According to optical and biomedical research and observation, no suppression of melatonin secretion was found in this golden LED indoor lighting, which also had the effect of reducing the incidence of xerophthalmia and conjunctivitis, speeding up the healing of damaged skin, and promoting hair regeneration. In addition, the light source has both the characteristics of warm color and high penetration of high pressure sodium lamps, and the characteristics of high efficiency of LED street lamps, and has been demonstrated and applied in more than ten cities in China.

Figure 11 Golden LED lighting application (a) Outdoor street lamp (Aixi Lake Park, Nanchang City) (b) Indoor atmosphere table lamp

In the visible light communication field, as a signal source, there is a major shortcoming of phosphor LEDs, that is, the carrier lifetime of phosphor PL far exceeds that of GaN–based LEDs, that is to say, the light pulses emitted by phosphors cannot be synchronized with high–speed switching LEDs, resulting in signal reception difficulty and low transmission rate; if the fluorescent component is filtered out, the signal intensity will decrease and the transmission distance will be short. Multi–primary color LEDs have no response delay problems, and each wavelength can be used as a signal transmission channel to send data, which greatly increases the transmission rate. 16 kinds of visible light LEDs with different wavelengths were selected and packaged into a device, as shown in Figure 12. An 8–color LED was used as the signal source for the underwater optical communication experiment, and a high transmission rate of 24.25GB/s was obtained with a transmission distance of 1.2m, being the highest underwater communication record for a single LED device at present.

In addition, there are also lots of application requirements for GaN–on–Si LEDs in plant lighting, aquaculture, photomedicine, and photobiology, and other field. Of course, many problems regarding GaN–on–Si LEDs also need to be solved, such as further improving long–wavelength luminous efficiency, obtaining narrower or wider spectra, and obtaining high luminous efficiency at any current densities. With the resolution of these problems and the continuous advancement of technology, GaN–on–Si LED and pure LED lighting technology will make great achievements in the future.

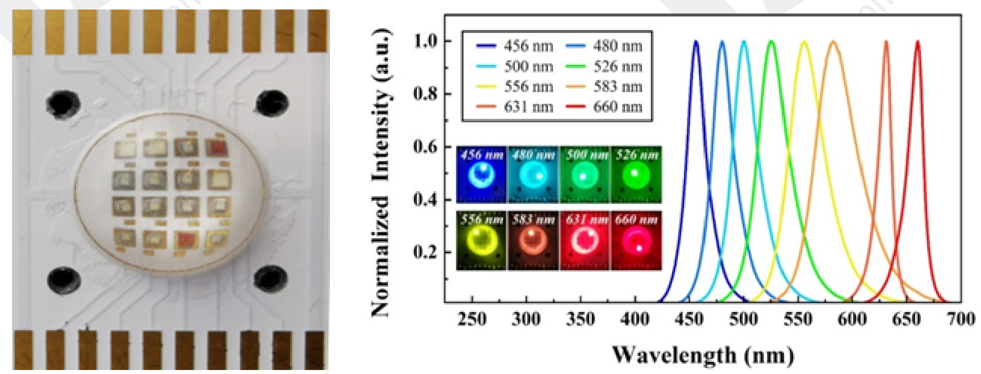

Figure 12 Multi-color pure LED optical communication chip