

Application Effects and Optimization Strategies of Semiconductor Lighting (LED) Technology in Agricultural Lighting

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Abstract: Traditional agriculture relies on sunlight or artificial light sources, which lacks large-scale, high-efficiency, and high-quality crop production. The development of semiconductor technology has led to the application of semiconductor lighting technology (LED) in agricultural lighting. LEDs are high-efficiency artificial light sources that can adjust spectrum, intensity, and photoperiod according to crop needs, effectively solving insufficient light and low efficiency problems in traditional agriculture. This paper studies the application scenarios and effects of LED technology in agricultural lighting and proposes optimization strategies to improve production efficiency, crop quality, and yield.

Keywords: LED, photosynthesis, plant light source, spectrum, agricultural lighting

1. Introduction

With the continuous growth of global agricultural production's demand for efficient and sustainable technologies, traditional agricultural lighting approaches, including sunlight and conventional artificial light sources, are no longer capable of satisfying the lighting requirements of crops during diverse growth phases. Semiconductor lighting technology (LED) has gradually become one of the key technologies of modern agricultural lighting systems due to its high efficiency, energy saving and adjustable spectrum, and has been widely used in agricultural production. This paper explores the application of LED technology in agriculture, highlighting its potential to enhance plant growth, yield, and quality. It evaluates the impact of LED lighting on crops and proposes optimization strategies, including spectrum optimization, light intensity and photoperiod adjustment, and intelligent control. The paper emphasizes the use of LED technology's adjustability to improve crop photosynthesis efficiency and overcome insufficient or uneven light. It offers an efficient, energy-saving, and adjustable lighting solution for modern agriculture, supporting improved crop yield and quality while reducing energy consumption, promoting sustainable agriculture development.

2. LED technical principles and agricultural lighting requirements

2.1. LED technology principles and characteristics

2.1.1. LED principle

LEDs are typically fabricated from semiconductor materials such as gallium arsenide (GaAs) and gallium nitride (GaN.). At their core lies a PN junction. There is a very narrow area without electrons or holes in the junction area of the PN junction follow Figure1. Under forward voltage, this area will shrink, and electrons and holes will begin to combine to form current. When electrons and holes are recombined, they can radiate visible light [1]. The color (wavelength) of the emitted light is contingent upon the band gap energy of the semiconductor material. Different materials and different doping methods can also produce different colors of light.

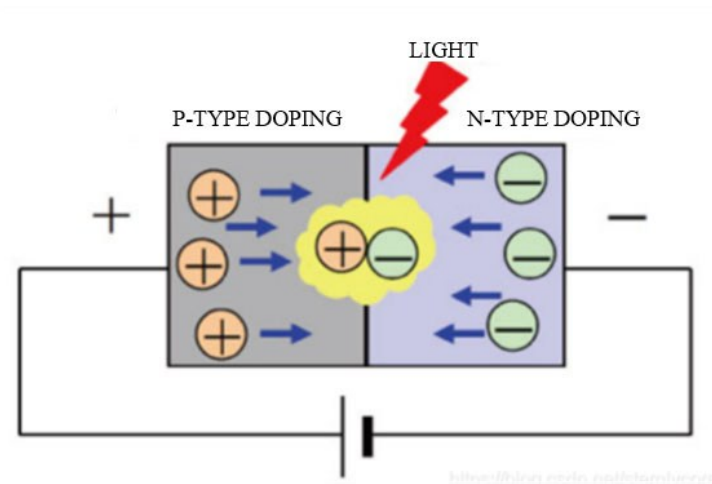


Figure 1: Structure of PN junction

2.1.2. LED simulation analysis based on COMSOL

To gain a more profound understanding of the characteristics and operating principles of LEDs, simulations are conducted using the COMSOL simulation software. Initially, within COMSOL, a 2D axisymmetric model, follow the steps below: define global variables, components, geometry modeling, mesh, and semiconductor initialization. After completion, you can get a 3D model as shown in Figure 2.

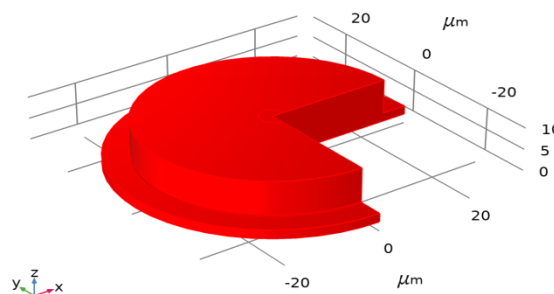


Figure 2: LED 3D model

In Figure 2, the upper surface of the cylinder is connected to the positive electrode, and the lower surface is connected to the negative electrode. After the simulation is completed, the volt-ampere characteristic curve of the LED three-dimensional model is drawn as shown in Figure 4.

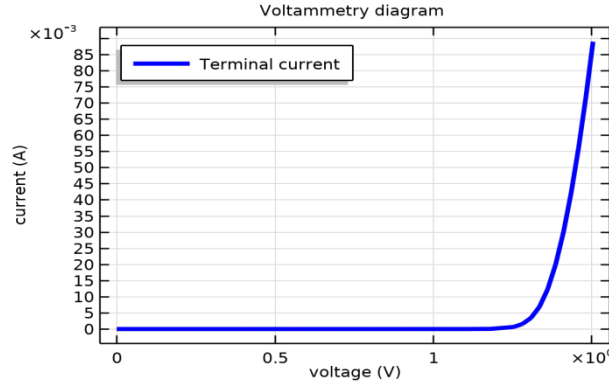


Figure 3: The volt-ampere characteristic curve of the LED model

In the left - hand portion of Figure 3, the LED current remains negligibly close to zero. This implies that under low - voltage conditions across the LED, there is an almost complete absence of current flow, placing the LED in the cutoff state. At around 1.5 V, when the voltage exceeds the threshold voltage, the slope of the curve suddenly increases, and electrons begin to jump from the n - type region to the p-type region. As a result, the current increases sharply and exhibits strong nonlinear characteristics.

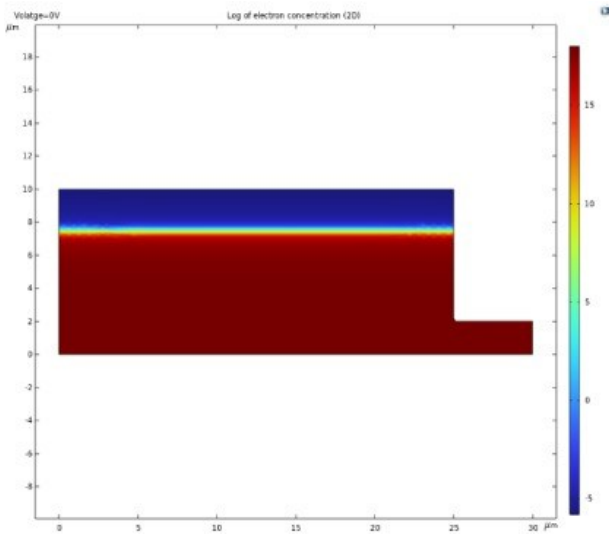


Figure 4: Electron concentration 2D at 0V

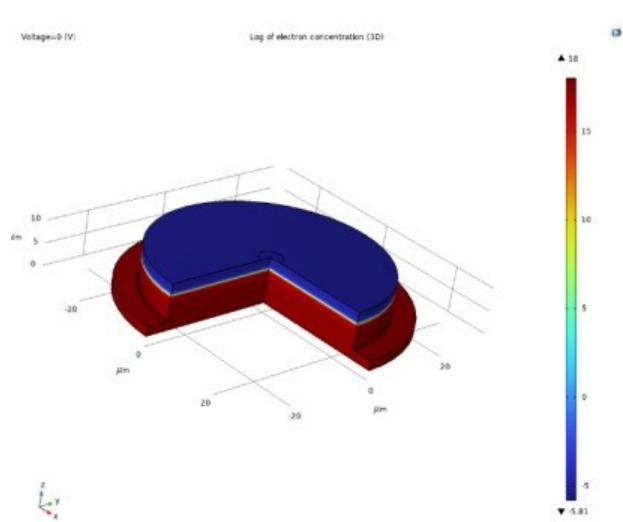


Figure 5: Electron concentration 3D at 0V

As depicted in Figure 4 and Figure 5. When the voltage is 0 V, the upper part is P-type doped. In this region, the hole concentration is greater than the electron concentration. and the bottom is N-type doped; the electron concentration is very high. In the current state, electrons and holes will only undergo a certain degree of recombination at the junction of the two, and there are basically no electrons in the LED that flow freely in the semiconductor, which is equivalent to the device being in the off state.

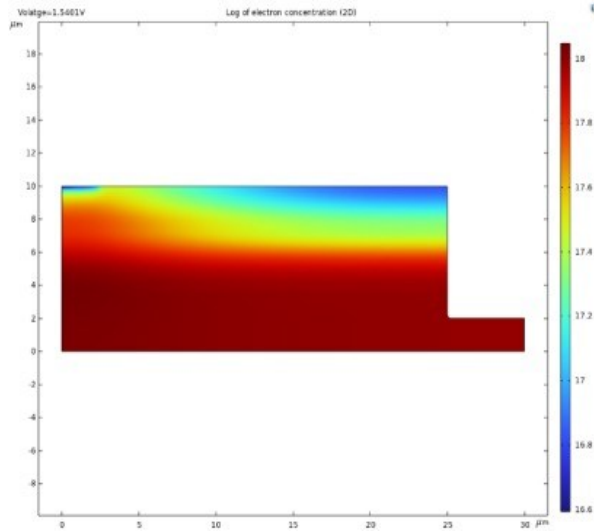


Figure 6: Electron concentration 2D at 0V

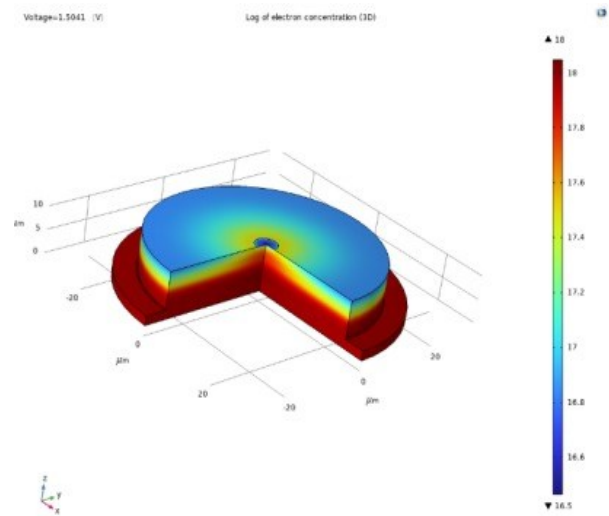


Figure 7: Electron concentration 3D at 0V

When the voltage exceeds the turn - on voltage, the electron concentration within the LED is illustrated in Figure 6 and Figure 7. Under the action of the forward voltage, the electrons in the N region move in the positive direction and enter the active layer. Simultaneously, holes in the P - region move in the opposite direction towards the active layer. Inside the active layer, electrons and holes are confined inside the active layer under the action of the heterojunction barrier. The electrons in the inverted population distribution undergo a transition effect, and when they recombine with holes, they emit the fluorescence that people see [2].

2.1.3. LED characteristics

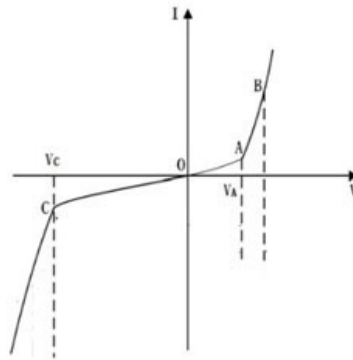


Figure 8: LED volt-ampere characteristic curve

The characteristics of an LED are primarily manifested in its volt - an ampere characteristic curve, which exhibits a nonlinear relationship. This curve can be generally described as follows: Firstly, at the LED turn - on voltage, the LED current is nearly zero, as represented by the OA segment in Figure 8. Then, once the voltage exceeds the turn - on voltage, that is, in the AB section of Figure 8, the current will increase rapidly, showing a nonlinear growth. Moreover, under reverse bias, the LED scarcely conducts electricity, presenting a very small current until it reaches the breakdown voltage, which is the CD segment in Figure 8.

2.2. Light requirements of plants

2.2.1. Photosynthesis of crops

The Photosynthesis of crops is a fundamental process in which light energy is harnessed to synthesize organic matter. This process is the basis for the growth and development of crops. Photosynthesis is the main way for plants to obtain energy. It converts light energy into chemical energy to provide the energy required for their growth, development and metabolism. Moreover, photosynthesis not only furnishes energy but also synthesizes a diverse array of organic substances essential for plants, such as glucose, starch, proteins, and fats, which are stored within the plants for various physiological functions.

2.2.2. Light requirements of crops

Light represents an essential prerequisite for the growth, development, maturity, fruiting and reproduction of crops. In recent years, it is generally believed that light quality, light intensity and photoperiod will affect plant photosynthesis, thereby affecting the growth and development of crops [3]. Light quality in agriculture impacts plant growth, photosynthesis, and morphology. Different wavelengths trigger physiological responses, affecting growth, blooming, fruit ripening, and stress tolerance. Chlorophyll exhibits two primary regions of maximum light absorption: red (640-660 nm) and blue (430-450 nm). Moreover, there exists an additional absorption region within the red - light spectrum, specifically at 700 to 750 nm [4].

2.3. Analysis of traditional agricultural lighting methods

Traditional agriculture uses sunlight and artificial light sources for lighting. Sunlight has a broad spectrum, including visible, ultraviolet, infrared, and X-rays. Plants primarily use blue and red wavelengths, absorbing only part of the light for photosynthesis. This disadvantages include poor light quality, intensity, and light cycle.

Light intensity represents a crucial factor influencing crop growth and development. Sunlight illumination is inevitably affected by local sunshine hours, climate, geographical location and other factors.

Traditional agriculture faces challenges due to the unstable and uncontrollable photoperiod. The seasonal variation in sunlight duration limits crop growth capacity and reduces photosynthesis efficiency. Traditional agriculture cannot use artificial lighting or other technologies to adjust the light cycle, resulting in low crop production efficiency. Alternatives like fluorescent lamps, high-pressure sodium lamps, metal halide lamps, and incandescent lamps have emerged as alternatives to sunlight, but they have problems such as low efficiency, non-adjustable spectrum, large size, and short life. Despite these challenges, artificial lighting devices have emerged as alternatives to traditional agriculture.

3. Current status of LED technology application in agricultural lighting

3.1. Application scope and scenarios

With the rapid development of modern agriculture, LED agricultural lighting has become an important means of efficient and high-quality production, and has obvious effects in increasing yield, improving quality, shortening cycle [5]. LED can be used in the following scenarios:

3.1.1. Greenhouse

In greenhouse agriculture, LED fill lights are used to provide the light needed for plant growth, especially in areas or seasons with insufficient light. Since the spectrum of LED lamps is adjustable, red light, blue light, ultraviolet light, etc. can be adjusted according to the needs of different plants to achieve optimal photosynthesis and promote plant growth [6].

3.1.2. Efficient monitoring of plant health

LED technology combined with sensors and intelligent control systems can monitor the light requirements and growth conditions of plants in real time and automatically adjust the light intensity and spectrum according to the health of the plants. For instance, Li Junyi from the University of Electronic Science and Technology of China developed an LED plant intelligent lighting solution and system that can monitor the growth status of plants in real time, provide relevant information such as plant diseases. By analyzing the light requirements of plants, it intelligently adjusts the lighting parameters of the system via Pulse - Width Modulation (PWM). In this way, it ensures that the lighting precisely matches the light requirements for the growth of the current plant species under its specific growth status [7].

3.2. Application case analysis

LED lighting technology has been widely used in plant factories. Plant factories are usually located in closed environments, like greenhouses, where LED supplementary lighting is employed to furnish stable lighting conditions, thereby enabling year - round production. For example, Canada's "Lufa Farms" plant factory uses LED supplementary lighting systems to cultivate crops such as tomatoes, strawberries, and leafy vegetables, achieving efficient and sustainable cultivation [6].

At the same time, the low heat characteristics of LED make it an ideal choice for greenhouse supplementary lighting. Compared with traditional light sources, it generates less heat when emitting light, so it can provide stable lighting without increasing the temperature in the greenhouse, which is beneficial for plant factories to control temperature and ensure that plants grow at the optimal temperature. The blueberry plant factory of Shanghai Blueberry Research Institute uses LED supplementary lighting software to identify crops in the plant factory and determine whether the crops have insufficient light or disease [8]. The LED supplementary lighting software system calculates the required LED light power based on plant growth environment parameters, such as temperature, humidity, CO₂ concentration, and crop physiological parameters. It performs real-time monitoring and analysis, adjusting output power and light cycle based on these results. This approach maximizes blueberry growth rate and enhances fruit quality, ensuring optimal photosynthesis [9].

3.3. Advantages and challenges in application

3.3.1. Advantages of LED applications in agriculture

The LED supplementary lighting software system calculates the required LED light power based on plant growth environment parameters, such as temperature, humidity, CO₂ concentration, and crop physiological parameters. It performs real-time monitoring and analysis, adjusting output power and light cycle based on these results. This approach maximizes blueberry growth rate and enhances fruit quality, ensuring optimal photosynthesis.

Finally, LED lighting technology can promote the growth and development of crops, enhance fruit quality, and boost stress resistance. By increasing indicators such as fruit sugar content and vitamin C, LED lighting can significantly raise crop yield and quality while also improving the fruit's

appearance. Additionally, appropriate LED lighting can facilitate the accumulation of plant secondary metabolites, such as flavonoids and anthocyanins, which have antioxidants and pest - resistance properties, contributing to enhanced plant stress resistance. Furthermore, LED lighting can activate the plant immune system, strengthening its drought resistance, cold resistance, and pest resistance [10].

3.3.2. Challenges of LED application in agriculture

The implementation of intelligent LED supplementary lighting systems in agriculture brings about several challenges. Firstly, there are challenges regarding system reliability and maintainability. Compared to traditional agriculture, intelligence typically implies a more intricate system. Once an intelligent LED supplementary lighting system is adopted, reliability becomes the primary challenge at hand. Specifically, modern lighting systems are expected to operate stably, be free from malfunctions, and be easy to maintain and upgrade during their operation [11]. Secondly, the cost poses a significant challenge. The price of a 28W ordinary fluorescent tube is approximately 20 yuan, whereas a 15W T8 agricultural LED plant growth lamp costs around 200 yuan, indicating a substantial price difference [12]. As a result, the large - scale adoption of LED intelligent lighting systems demands a substantial initial investment, which has emerged as one of the crucial factors restricting the application of LEDs in agriculture.

4. Analysis of the application effect of LED technology in agricultural lighting

4.1. Effects on plant growth and development

LED supplementary lighting technology can solve the problems of uneven, unstable and uncontrollable lighting in traditional agriculture. In order to verify the effect of LED supplementary lighting on grapes, Shenyang Agricultural University conducted the following research: experiments were conducted on the two varieties of grapes, 'Autumn Black' and 'Sunshine Rose', from multiple aspects such as new shoot thickness and internode spacing, leaf growth indicators (such as leaf size, leaf chromaticity, leaf thickness, chlorophyll content), as well as light and parameters. They were divided into four categories: a control group and three groups irradiated with LED supplementary lights with different red-to-blue ratios (2:1, 3:1, and 6:1, respectively).

Experiments show that LED lighting can improve the root vitality of grape plants. LED lighting has the following effects on the above parameters: 1) significantly increase the stem thickness of new grape shoots 2). It deepens the color of grape leaves, making the leaves appear greener and darker. 3) It boosts the chlorophyll content of grape leaves. The LED lighting experimental group increased the chlorophyll content by about 20.11% compared with the control group. 4) The net photosynthetic rate increased by about 13%. The experiment also found that LED lighting enhanced the transpiration of grape water and increased stomatal conductance.

4.2. Impact on agricultural product yield and quality

The study also pointed out the impact of LED supplementary lighting measures on the quality of grapefruit. The experiment used the 'Autumn Black' and 'Sunshine Rose' grape varieties as test materials to investigate and compare the fruit development, color, anthocyanin content, etc. under different light qualities [13].

Experiments have shown that supplementary lighting can significantly improve the appearance and internal quality of grapes. In the fruit quality test of "Autumn Black" grapes, the skin color, single fruit weight and single grain diameter of the group treated with the No. 3 light all showed significant improvements. The article points out that LED supplementary lighting can increase the soluble solids

content and vitamin C content of grapes, which shows that LED supplementary lighting technology accelerates the accumulation of sugar in grapes by promoting the enhancement of photosynthesis.

4.3. Analysis of economic and environmental benefits

4.3.1. Economic benefits

LED light sources can be customized according to the spectral requirements of crops, providing optimal lighting conditions, promoting plant photosynthesis and growth, and thus increasing crop yields. By controlling light at different stages, the growth cycle of crops can be shortened, and growers can get benefits faster.

4.3.2. Environmental benefits

Energy saving and consumption reduction: The widespread use of LED lighting technology can seek new opportunities and high energy consumption solutions in the current agricultural lighting market and accelerate the development of China's new agriculture [1]. Compared with traditional agricultural lamps, LED lamps have the advantages of low heat generation, small size, and long service life. They have obvious advantages in environmental benefits. By employing intelligent LED lighting systems to monitor plant diseases, it becomes possible to mitigate the occurrence of plant diseases through adjustments in light quality, photoperiod, and other factors. Therefore, the use of LED lighting can reduce the use of pesticides and fertilizers when cultivating crops, help achieve sustainable agricultural production, and embody the concept of green and environmentally friendly development.

5. Conclusion

This paper focuses on the application effects and optimization strategies of semiconductor lighting (LED) technology in the field of agricultural lighting, aiming to explore how to use the characteristics of LED such as adjustable spectrum, light intensity and photoperiod to solve the problems of insufficient light, low efficiency and uncontrollable light in traditional agriculture, thereby improving crop yield, quality and production sustainability.

This paper discusses the benefits of LED technology in the agricultural field, highlighting its ability to improve crop production efficiency and promote sustainable development. LED technology enhances photosynthesis efficiency by controlling the spectrum, light intensity, and photoperiod, increasing crop yield and quality. It also shortens the crop growth cycle, reduces pesticide use and energy waste, and promotes green and sustainable agricultural development. Compared to traditional light sources, LED has high efficiency, low heat generation, and long life, reducing energy consumption and maintenance costs. Combining LED with intelligent control systems like neural networks and Internet of Things systems provides a precise light environment management solution for plant factories and greenhouses. However, the article has limitations, including limited coverage of specific crops, insufficient analysis of cost and system reliability, and a bottleneck in LED technology. Future research should focus on expanding experiment scope, deepening economic research, and advancing LED technology by researching new packaging materials, lightweight algorithms, and high-reliability hardware. By promoting the deep integration of LED technology and agricultural production, it is expected to support the quality, efficiency, and sustainable development of modern agriculture.

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