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Scientific Content Analysis of Light-emitting Diode (LED) for High School Physics STEM-based Learning

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Abstract

The embedded STEM approach is currently the most easily implemented STEM approach in Indonesia compared to other types of approaches. This approach requires a context to be delivered in the learning process. The selection of context must consider its relevance to everyday life and closely linked to process competencies. This study conducts a scientific content analysis of Light Emitting Diode and investigates its potential application in high school physics embedded-STEM learning. The research adopts a descriptive qualitative methodology using the Model of Educational Reconstruction as the research framework. Data were collected through a literature review of three scientific references on LEDs. The scientific content analysis of LEDs was performed using the hermeneutic analysis method. The literature analysis of these subthemes revealed that the major Physics concepts relevant to LEDs include energy and its transformations, direct current electricity, electromagnetic radiation, electronic systems, and quantum physics. Consequently, LEDs hold significant potential as a context for embedded STEM learning in high school Physics. The results of this study provide a foundation for the subsequent phase of constructing embedded STEM learning designs with the topic of LEDs, such as the development of textbooks, learning strategies, and their evaluation.

Keywords: contextual physics, LED, embedded STEM

INTRODUCTION

STEM education has become a global educational trend. For several decades, STEM education has been developed and implemented in various countries such as the United States, the United Kingdom, Australia, Finland, Thailand, and Malaysia (Winarni, Zubaidah & Koes, 2016). In Indonesia, numerous studies on STEM education have been conducted over nearly a decade (Syukri, Halim & Mirah, 2013). However, most of these studies have been carried out at the elementary education level. This can be understood because implementing full STEM learning is relatively easier at the elementary level compared to the middle and high school levels. This is due to the thematic integrated curriculum in elementary schools (Roberts, 2012). Additionally, each class level is taught by a single teacher, unlike in middle or high schools, where the curriculum is not thematic (subjects are still separate) and each subject is taught by different teachers. Therefore, implementing STEM learning in high schools faces greater challenges compared to elementary schools.

Restructuring the entire curriculum is not a practical and easy option. The most feasible option to integrate STEM without restructuring the curriculum is through the embedded STEM approach (Chen, 2001; Roberts, 2012). This approach requires a context (functional, social, or cultural) as a means to deliver the domain knowledge to students (Chen, 2001). This aligns with the view that STEM education intersects with context-based learning (Sutaphan & Yunyeong, 2019). Thus, developing STEM learning with a context-based approach necessitates studies related to the context to be used.

LEDs are a potential context for STEM learning in high school physics subjects because LEDs are commonly found in everyday objects used by students such as TVs, lamps, and mobile phones. Etkina and Planinšič stated that LEDs have been widely used in physics education as tools to demonstrate physical phenomena in daily life (Etkina & Planinšič, 2014). Additionally, LEDs relate to several physics concepts such as electric fields and the motion of charged particles in electric fields, the photoelectric effect, and DC circuits.

Based on studies of similar research on contextual learning development, the Model of Educational Reconstruction (MER) is a common framework used to reconstruct relatively new contexts in science or those not yet in the school curriculum (Karim, Saepuzaman & Sriyansyah, 2016; Anugrah, Mudzakir & Sumarna, 2017; Kersting, et al, 2018; Nursa'adah, 2018). MER consists of three components: 1) clarification and analysis of scientific content, 2) research on the learning process, and 3) design and evaluation of the learning process (Duit, et al, 2012). Previous studies have not specifically examined the LED context for high school physics learning. Therefore, this study aims to reconstruct the education of the LED context for high school physics learning. However, this reconstruction process is limited to the first stage, which is the clarification and analysis of the scientific content of the LED context. This is because, according to Anugrah in his research on the scientific analysis of batik context, this stage is fundamental and needs to be thoroughly conducted as a basis for subsequent stages (Anugrah, et al, 2021). Therefore, this study focuses on clarifying and analyzing the scientific content of LEDs and related high school physics concepts. The results can be used in further research related to the development of STEM learning in high school physics, such as developing teaching materials, media, strategies, and evaluation of physics learning with LED contexts.

RESEARCH METHOD

This study used a descriptive qualitative method. The analysis of the scientific content structure of the LED context was conducted through a literature review of textbooks and journal articles about LEDs. After clarifying the scientific content of LEDs, an analysis of high school physics concepts related to LED scientific content was conducted. The reference used in this research phase is Learning Outcomes from *Kurikulum Merdeka*. The instruments developed and used for data collection are detailed in Table 1 below.

Table 1. Research Instruments for Analyzing Scientific Perspective of LED

Research Question	Instrument	Data Obtained
Scientific perspective on LED context	Book and journal article analysis format on LED context	Raw manuscript on LED context
High school physics concepts related to LED scientific content	Analysis format of high school physics concepts related to LED context	High school physics concepts related to LED

The analysis of the LED scientific content structure was conducted based on the hermeneutic analysis method as described by Katmann for the scientific clarification of the selected context (Kattmann, et al, 1996). This analysis includes: 1) high school physics concepts related to LEDs, 2) limitations in explaining LEDs for high school levels, 3) social and ethical implications related to these scientific concepts, and 4) applicable fields influenced by these concepts.

FINDINGS & DISCUSSION

Scientists' Perspective on the LED Context

The scientists' perspective on the LED context was obtained through a literature study from three references related to LEDs. From these references, scientific information related to the LED context was obtained. The results are detailed in Table 2 below.

Table 2. Literature Analysis on the LED Context

No	Title	Author(s)	Content
1	Fundamentals of Solar Cells and Light-Emitting Diodes	Wang, Liu dan Gao (2019)	Electroluminescence principle; LED work principle
2	Light-emitting diodes: Second Edition	Schubert (2006)	LED electrical properties; emission energy; emission spectrum
3	Light-emitting Diodes (LED)	Rahman (2012)	Introduction to LEDs; LED emitting process; how LEDs work; LED light color

The literature study results were then processed and systematically compiled into a basic text on LEDs. This text begins with an introduction to LEDs, followed by a discussion on the principles of light emission in LEDs, components, and working principles of LEDs. Detailed discussions on the scientists' perspective on the LED context are elaborated in the subsections below.

Introduction to LED

LED (light-emitting diode) is an electronic component composed of semiconductor diodes that can emit light (Singh, 2009). A diode is an active component with two poles that function analogously to a valve, allowing current to flow in one direction but blocking it in the opposite direction. The first LED was reported in 1928 by Oleg Vladimirovich Losev, where light emission was observed in inorganic semiconductor Si-carbide (Zheludev, 2008). The color of light produced by LEDs is determined by the energy gap between the valence band and the conduction band of the emitter. However, LED lighting also depends on the amount of electrical current applied (Wang, Liu & Gao, 2019).

An LED (Light Emitting Diode) comprises two legs made from a type of wire. The longer wire is the anode, while the shorter wire is the cathode. The anode is an electrode (metal or other conductive material) in an electrochemical cell that becomes polarized when current flows into it. Conversely, the cathode is an electrode that becomes polarized when electric current flows out of it. LEDs offer several advantages, including:

- Higher energy efficiency compared to other types of lamps (energy savings of 80-90%)
- Longer lifespan, reaching up to 100,000 hours
- Low operating DC voltage requirement
- Cool light output (no UV radiation or thermal energy)
- Small and compact size
- Availability in various colors
- Cost-effectiveness.

However, LEDs also have some disadvantages, including:

- High ambient temperatures can cause electrical disturbances in LEDs
- The cost per lumen is higher compared to other lamps
- The light intensity produced is relatively low (Rahman, 2012).

Light emission in LEDs occurs through the process of electroluminescence (EL), which is the emission of light caused by the presence of an electric current. This process refers to the electro-optical conversion process in which a semiconductor emits light in response to the injection of an electric current. In the EL mechanism, holes and electrons are separately injected into the valence and conduction bands of the semiconductor, where they recombine and release their energy as photons—light (Wang, Liu & Gao, 2019).

LED Components

The basic structure of an LED device consists of an emitting layer sandwiched between a transparent conductive oxide and a metal electrode. The basic structure of an LED device is depicted in Figure 1 below. Functional layers such as the hole injection layer (HIL), hole transport layer (HTL), electron injection layer (EIL), and electron transport layer (ETL) can be utilized to provide balanced hole and electron injection and transport, forming a multilayer LED. In some cases, the hole blocking layer (HBL) and electron blocking layer (EBL) are also incorporated into the multilayer LED because these blocking layers can prevent carrier leakage of opposite charge carriers, thereby enhancing efficiency. Despite the complexity in device fabrication, multilayer LEDs serve as a robust platform with a broader scope for device optimization.

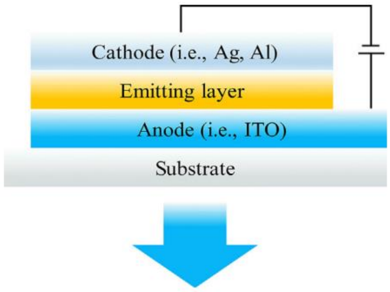

Figure 1. Basic structure of LED (Wang, Liu & Gao, 2019)

Most reported LEDs are bottom-emitting devices, where light is emitted from the side of the substrate. However, for practical applications, it would be preferable for light to be emitted from the last deposited layer, referred to as top-emitting LEDs. Top-emitting LEDs allow for easier integration with backplane electronics such as active matrix Si, but they require the use of transparent top electrodes instead of the classic opaque metal cathodes. New, thin, transparent electrodes are needed to replace ITO, which would damage the underlying layers during deposition.

Another commonly used device structure is the tandem structure, where multiple light-emitting units are connected by p-n connectors. This tandem structure can be seen in Figure 2. Tandem LEDs can significantly increase light efficiency by generating multiple photons per injected charge unit. Consequently, tandem LEDs are also known as multi-photon emission (MPE) LEDs. Considering that standard multilayer LEDs have a specific current I0 and voltage V0, tandem devices with N light-emitting units, similar to standard LEDs, will require approximately I0/N current and V0N voltage, respectively, to achieve the same brightness. Therefore, power consumption will be the same in tandem LEDs, and tandem device structures typically do not enhance power efficiency. If the unit connectors require additional voltage drop, power consumption will be higher than that of standard multilayer LEDs.

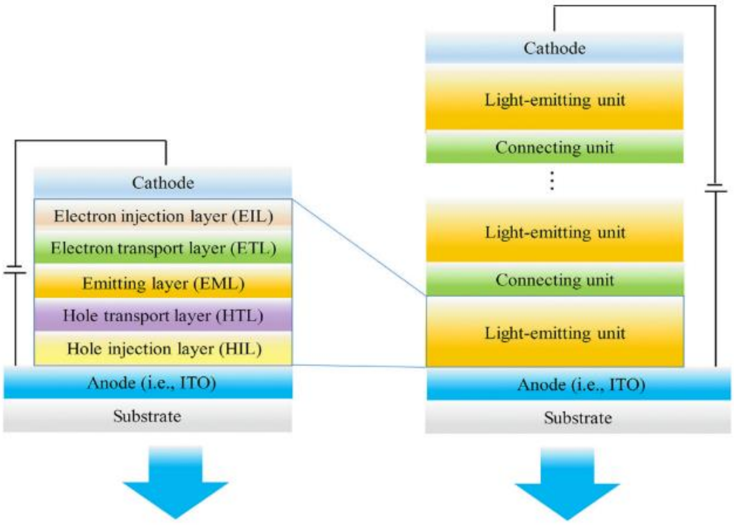

Figure 2. Structure of standard multilayer (left) and tandem (right) LED (Wang, Liu & Gao, 2019)

Fortunately, it is posible to achieve lower power consumption (and consequently higher power efficiency) of tandem structures by optimizing the unit connectors. More importantly, tandem structures can improve operational lifetime because current density is reduced, with device aging typically being superlinear (cubic, or even quadratic). Additionally, tandem-structured devices exhibit fewer short-circuit defects. Despite these advantages, tandem LEDs face challenges in forming reliable hole injection (HI) contacts for the top light-emitting units. The use of transparent ITO electrodes as part of the connecting units is effective; however, ITO deposition causes sputtering damage to the underlying layers, and its high conductivity leads to cross-talk issues. Moreover, tandem LED structures are quite complex, increasing the fabrication difficulty, particularly for solution-processed LEDs.

Principles of LED

Light is a form of energy produced by photons. Photons are released as a result of electron movement. Within an atom, electrons move in orbitals surrounding the nucleus. Electrons in different orbitals have varying amounts of energy. In other words, electrons with higher energy move in orbitals farther from the nucleus. An electron releases energy when it transitions from a higher orbital to a lower one. This released energy is in the form of photons. As we know, free electrons moving across a diode can fall into the empty holes of the p-type layer. This affects the conduction band towards the lowest orbital. Consequently, electrons release energy in the form of photons (Rahman, 2012).

The energy of photons emitted from a semiconductor with an energy gap, E_g, is given by the band gap energy, which is:

$$hv \approx E_g$$

In an ideal diode, each electron injected into the active region will produce a photon. Energy conservation thus requires that the energy with which the electron is injected equals the photon energy. Therefore, energy conservation necessitates:

$$eV = hv$$

This means that the voltage applied to the LED, multiplied by the elementary charge, equals the photon energy. Several effects can alter the diode voltage from the ideal value (Schubert, 2006). LEDs come in many colors, including red, yellow, blue, green, white, and white (infrared), each with its characteristics and used according to specific needs. LEDs are made from n-type semiconductor material in the valence band and p-type in the conduction band, separated by a depletion region. In the conduction band, there are more holes, and in the valence band, there are many electrons. When forward bias voltage is applied, a diffusion current causing holes appears. When the circuit's positive pole is connected to the n-type layer and the negative pole is connected to the p-type layer, free electrons gather at one diode pole, and holes gather at the other pole. The depletion region becomes larger. Holes move to the n-type, and electrons in the n-type move to the p-type, causing current flow. When recombination current occurs (diffusion and drift current appear), some electrons will recombine with holes, producing energy in the form of photon light (LED color emission), while the rest will generate heat energy. The illustration can be seen in Figure 3.

The energy of a photon will be proportional to the energy difference between the conduction band and the valence band (band-gap energy). The wavelength of the emitted photon is

$$\lambda = \frac{c}{f} = \frac{c}{E_g/_h} = \frac{hc}{E_g}$$

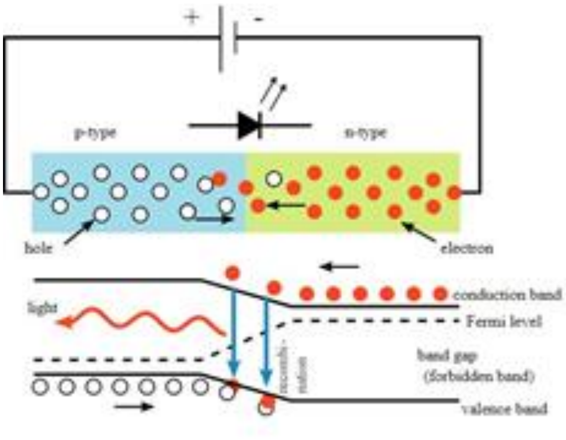

Figure 3. The occurrence of a depletion area due to the polarization of holes at one pole and electrons at the other pole (Rahman, 2012)

Unlike standard signal diodes designed for rectification and made from germanium or silicon, LEDs are made from exotic semiconductor compounds such as Gallium Arsenide (GaAs), Gallium Phosphide (GaP), Gallium Arsenide Phosphide (GaAsP), Silicon Carbide (SiC), or Indium Gallium Nitride (GaInN), mixed in various ratios. The precise mixing of semiconductor materials used results in different energy gaps between the conduction band and the valence band. Consequently, different wavelengths of light are produced, determining the color emitted by the LED. For example, LEDs on the market designed for visible regions commonly use gallium due to its compatibility with arsenic and phosphorus atoms. The composition consists of 60% non-gallium, occupied by arsenic, and 40% by phosphorus ions, resulting in a band gap energy (E_g) of 1.8 eV. This band gap energy produces red light.

The physical mechanism by which semiconductor LEDs emit light is the spontaneous recombination of electron-hole pairs and simultaneous photon emission. The spontaneous emission process fundamentally differs from the stimulated emission process occurring in semiconductor lasers and superluminescent LEDs. Spontaneous recombination has specific characteristics that determine the optical properties of LEDs. The properties of spontaneous emission in LEDs will be discussed in this section.

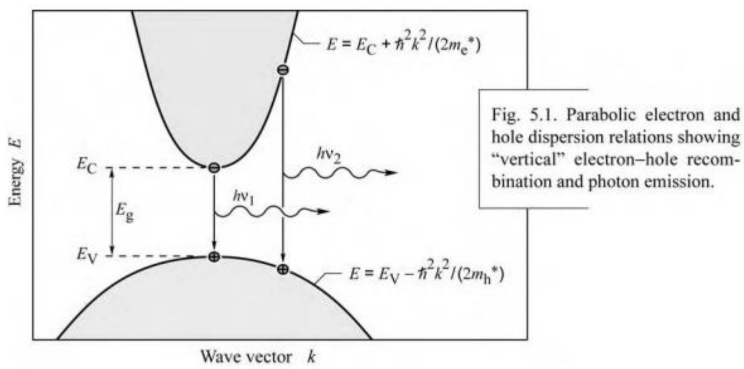

Figure 4. Parabolic electron-hole dispersion (Schubert, 2006)

The electron-hole recombination process is schematically illustrated in Figure 4. Electrons in the conduction band and holes in the valence band are assumed to have a parabolic dispersion relationship:

$$E = E_C + \frac{h^2k^2}{2m_e^*} \qquad \text{(for electron)}$$

$$E = E_V - \frac{h^2k^2}{2m_h^*} \qquad \text{(for hole)}$$

where $2m_e^*$ and $2m_h^*$ are the effective masses of electrons and holes, h, is Planck's constant divided by 2π, k is the wave number of the carriers, and E_V and E_C are the edges of the valence and conduction bands, respectively.

The requirements for energy and momentum conservation lead to further insights into the mechanism of radiative recombination. According to the Boltzmann distribution, electrons and holes have an average kinetic energy of kT. Energy conservation dictates that the energy of the photon is given by the difference between the electron energy, E_e, and the hole energy, E_h, which is

$$hv = E_e - E_h \approx E_g$$

The photon's energy is approximately equal to the band gap energy, E_g, if the thermal energy is small compared to the band gap energy $kT << E_g$. Therefore, the desired emission wavelength of the LED can be achieved by selecting a semiconductor material with an appropriate band gap energy. For instance, GaAs has a band gap energy of 1.42 eV at room temperature and thus a GaAs LED emits at an infrared wavelength of 870 nm.

It is useful to compare the average momentum of the carrier with the photon momentum. A carrier with kinetic energy kT and an effective mass $m*$ has momentum

$$p = m \times v = \sqrt{2m \times \frac{1}{2} m \times v^2} = \sqrt{2m \times kT}$$

The momentum of a photon with energy \(E_g \) can be derived from the de Broglie relation:

$$p = hk = \frac{hv}{c} = \frac{E_g}{c}$$

Calculations of carrier momentum and photon momentum show that the carrier momentum is an order of magnitude greater than the photon momentum. Thus, the electron momentum cannot change significantly during the transition from the conduction band to the valence band. Consequently, the transition is "vertical", meaning the electron recombines only with a hole that has the same momentum or k-value.

Using the requirement that the electron and hole momenta are the same, the photon energy can be written as a combined dispersion relation:

$$hv = E_C + \frac{h^2k^2}{2m_e^*} - E_V - \frac{h^2k^2}{2m_h^*} = E_g + \frac{h^2k^2}{2m_r^*}$$

where $mr*$ is the reduced mass given by

$$\frac{1}{m_r^*} = \frac{1}{m_e^*} + \frac{1}{m_h^*}$$

Using the combined dispersion relation, the joint density of states can be calculated and obtained as

$$\rho(E) = \frac{1}{2\pi^2}\left(\frac{2m_r^*}{h^2}\right)^{3/2}\sqrt{E - E_g}$$

The distribution of carriers in the allowed band is given by the Boltzmann distribution, i.e.,

$$f_B(E) = e^{-E/kT}$$

The emission intensity as a function of energy is proportional to the product of the above equations.

$$(E) \infty \sqrt{E - E_g}\, e^{-E/kT}$$

The maximum emission intensity occurs at

$$E = E_g + \frac{1}{2}kT$$

The full width at half maximum of the emission is

$$\Delta E = 1.8kT \quad \text{or} \quad \Delta\lambda = \frac{1.8kT\,\lambda^2}{hc}$$

For example, the theoretical room temperature linewidth of a GaAs LED emitting at 870 nm is E = 46 meV or = 28 nm.

The spectral linewidth of LED emission is significant in several ways. Firstly, the emission linewidth of an LED in the visible range is relatively narrow compared to the entire visible spectrum range. LED emission is even narrower than the spectral width of a single color as perceived by the human eye. For instance, the red color range in wavelength spans from 625 to 730 nm, which is much wider than the typical LED emission spectrum. Therefore, LED emission is perceived by the human eye as monochromatic.

Secondly, optical fibers are dispersive, leading to different propagation speeds for light pulses composed of various wavelengths. Material dispersion in optical fibers limits the "bit rate × distance product" achievable with LEDs. The spontaneous carrier lifetime in LEDs in direct-gap semiconductors is on the order of 1-100 ns, depending on the doping concentration of the active region (or carrier concentration) and the material quality. Thus, modulation speeds up to 1 Gbit/s can be achieved with LEDs (Schubert, 2006).

High School Physics Concepts Related to LED

High school physics concepts that can explain the scientific content in the context of LEDs, as previously described in the subsection. The analysis of these high school physics concepts related to the context of LEDs is conducted with reference to the Content Standards for high school physics subjects. The results of this analysis are presented in Table 3 below.

Table 3. Scientific perspective of LEDs and its related high school physics concepts

No	Context	Content
1	LED Development	Energy Transformation
2	LED Definition	Electric Current
		Light as Electromagnetic Wave
3	LED Structure	Electric Charge and Behavior on Conductors and Insulators
		Electric Current
		Distinguishing DC and AC
4	LED Working Principle	Electrical Circuit Characteristics
		Electromagnetic Induction Phenomenon
		Distinguishing DC and AC
		Electromagnetic Radiation
		Light as Electromagnetic Wave
		Light as a Component of Radiation

From the table above, it can be observed that the high school physics concepts capable of elucidating the scientific content of LEDs are: energy and its transformations, direct current electricity, electromagnetic radiation, electronic systems, and quantum physics.

CONCLUSION

To use the context of LEDs in high school STEM Physics learning, a reconstruction process is first required so that the context can be tailored to students according to their cognitive levels. The initial stage of this reconstruction involves a literature review to unearth the scientific content related to LEDs, including their definition, components, and operational principles. This stage is necessary to analyze high school Physics concepts related to LEDs. From this study, it is known that high school Physics concepts related to LEDs include energy and its transformations, direct current electricity, electromagnetic radiation, electronic systems, and quantum physics. The findings of this study are crucial for advancing to the subsequent stage of reconstructing the LED context in high school Physics learning, which involves investigating the perspectives of both students and teachers, as well as developing learning instruments such as textbooks, strategies, and assessments.

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