Light-Emitting Diodes: Learning New Physics

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This is the third paper in our Light-Emitting Diodes series. The series aims to create a systematic library of LED-based materials and to provide the readers with the description of experiments and pedagogical treatment that would help their students construct, test, and apply physics concepts and mathematical relations. The first paper, published in the February 2014 issue of *TPT*,[1] provided an overview of possible uses of LEDs in a physics course. The second paper[2] discussed how one could help students learn the foundational aspects of LED physics through a scaffolded inquiry approach, specifically the ISLE cycle. The goals of this paper are to show how the activities described in our second paper help to deepen student understanding of physics and to broaden student knowledge by exploring new phenomena such as fluorescence. Activities described in this paper are suitable for advanced high school courses, introductory courses for physics and engineering majors, courses for prospective physics teachers, and professional development programs.

In the second paper in the LED series,[2] we discussed how to use the ISLE cycle to help students construct the following basic ideas relevant to LED physics:

a) LEDs are small (point) light sources embedded in a plastic dome;
b) LEDs have an asymmetric *I*-*V* curve;
c) LEDs produce light of one color (i.e., has narrow band spectrum);
d) Turn-on voltage of LED is related to the color it emits;
e) LEDs are composed of semiconductor materials;
f) LEDs can either convert electric energy to light energy (acting as "loads" in an electric circuit) or convert light energy into electric energy (acting as solar cells in an electric circuit).

Students learned these ideas following the ISLE cycles[3] that consist of conducting observational experiments, collecting and analyzing data, explaining the patterns in the data (devising multiple explanations) and testing those explanations by using them to predict the outcomes of the new (testing) experiments, and comparing the outcomes to the predictions. In this paper we will consider those ideas developed and tested by the students, and we will use them to (1) develop new ideas and (2) apply those tested ideas to explain new phenomena.[4]

Activities described in this paper were conducted with high school students in Slovenia, freshman physics majors at the University of Ljubljana, and with pre-service physics teachers at Rutgers University. Selected activities were conducted with New Jersey high school students. "Possible" students' explanations described in the paper are the explanations proposed by the students who participated in the activities.

Using LEDs to deepen student understanding of traditionally taught physics concepts

In this section we will focus on investigating phenomena and devices that students learn about in any physics course. We will show how the use of LEDs will allow the students not only to investigate at a deeper level the phenomena with which they are already familiar, but also to discover and study the phenomena that they might not otherwise meet in a general physics course.

LED as a source of electric energy

Physics Education Research shows that one of the difficulties that students encounter while studying dc circuits is the concept of a battery as a constant (or almost constant) voltage source and not as the source of constant current (as many students believe).[5] There are many curriculum materials that help students develop the correct understanding that the battery is a constant voltage source.[6] We hypothesize that the students will be able to solidify their understanding of conventional batteries if they have an opportunity to compare/contrast them with constant current sources. An LED illuminated by an external source of light is an example of a constant current source. Below we show how we can help students "discover" this idea.

In the previous paper we discussed activities and reasoning that would lead students to the understanding that an LED can work as a solar cell. Here we will start the cycle with those activities. We will assume that students understand how an LED works (activities to develop this understanding are in our second paper[2]).

Equipment: A two-LED unit (see Fig. 1), an ammeter, and various resistors (for values see graphs in Fig. 2).

Students working in groups perform the following activities.

1. Observational experiment: Switch on the two-LED unit by clipping the crocodile clip to the free end of LED

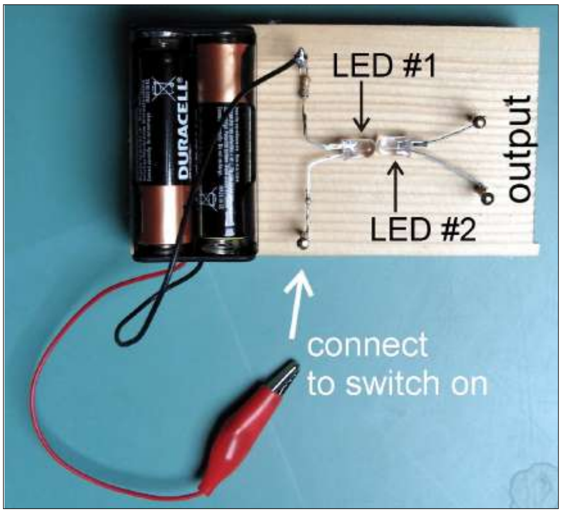

Fig. 1. A two-LED unit that consists of a light source LED (#1) and a resistor (8 Ω in our case) connected to a 3.0-V battery, and the second LED (#2), which is not connected to a battery but it is illuminated by LED #1.[7] In our case the yellow LEDs proved to be the best choice (largest power output).

#1 (see Fig. 1). Connect a 50-Ω resistor and an ammeter in series with LED #2. Record the ammeter reading when LED#1 is off and when it is on.

2. ***Explanation:*** Explain the reading of the ammeter in those two cases.
3. ***Patterns and explanations:*** Investigate the properties of LED #2 when it is acting like a solar cell. Specifically, vary the resistance of the load and measure the current through LED #2 and voltage across it. Create a graph $I(R)$ and describe the pattern you see in the shape of the graph.
4. ***Testing experiments:*** Propose experiments to test your explanation(s). After you design the experiment, make a prediction based on the idea under test and only then conduct the experiment.
5. ***Explanation:*** Try to come up with a mechanism behind your finding that an LED works as a constant current source.

The students start by illuminating LED #2 with LED #1 and observing that the ammeter connected to LED #2 shows a nonzero reading. Students will easily devise a causal explanation for this observation—the LED #2 is acting like a solar cell. As this activity was described in our paper #2, we will not discuss here how students might test this idea. Let's assume that they followed the procedure described in that paper. The next step is to investigate properties of a solar cell, specifically, the dependence of the current through the load on the resistance of the load. The results of such an investigation are shown in Fig. 2(a).

Analyzing the data that students collected, they will come up with the idea (explanation) that when a load resistor is smaller than about 70 kΩ, the LED behaves approximately as a constant current source. For resistors larger than 70 kΩ, the LED source is not able to maintain constant current any more. In order to investigate further the performance of the LED as a power source, students can use previous data to produce graphs of the power of the load versus load resistance $P(R)$[Fig. 2(b)] and current through the LED versus voltage across the LED $I(V)$ [Fig. 2(c)]. The graph $P(R)$ shows an important property of solar cells: the power depends on the resistance of the load and it is the greatest for a particular load.

To test the idea that an LED is a constant current source, the students can design experiments and make predictions about their outcomes using their new knowledge of LEDs and their knowledge of dc circuits. Two testing experiments that students can come up with are shown below. Note the reasoning that you might want your students to use here: *If* the LED is a source of constant current (the hypothesis), *and* we first connect resistor #1 in series to it, and then add resistor #2 in series with #1 (setting up the experiment), *then* the current through #1 when it is alone and when it is connected to #2 should be the same. A voltmeter connected across resistor #1 should show the same reading in both experiments (prediction of the outcome of the experiment). This outcome should be contrasted with the familiar case when the same circuits are connected to an ideal battery—a constant voltage source. Adding resistors in series should decrease the current through the circuit and consequently the voltmeter readings across the single resistor (prediction). We can repeat similar reasoning for the case of resistors in parallel. The outcomes of all testing experiments match the predictions based on the idea that the LED is a constant current source. See Figs. 3(a) and 3(b).

The next step for the students is to devise a mechanistic explanation for why an LED behaves like a constant current source. Students may need help at this point, i.e., have a reminder of the microscopic structure of the LED. The key here is the constant illumination of LED #2 in the experiments. When an LED is illuminated by a constant light source, there is a constant flux of incident photons, which means that the number of hole-electron pairs created per second is constant. When you connect

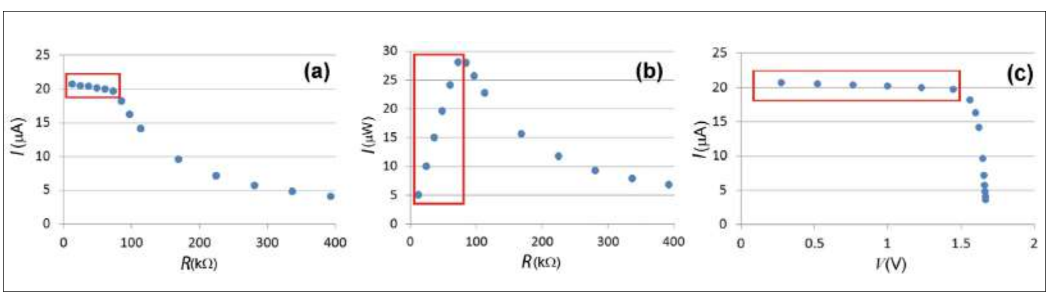

Fig. 2. Performance of a yellow LED as a solar cell: (a) current through the load vs load resistance, and (b) power of the load vs load resistance, and (c) current through vs voltage across the LED. Red rectangles indicate the range in which the LED behaves approximately as a constant current source. Error bars are about the size of the dots on the graphs.

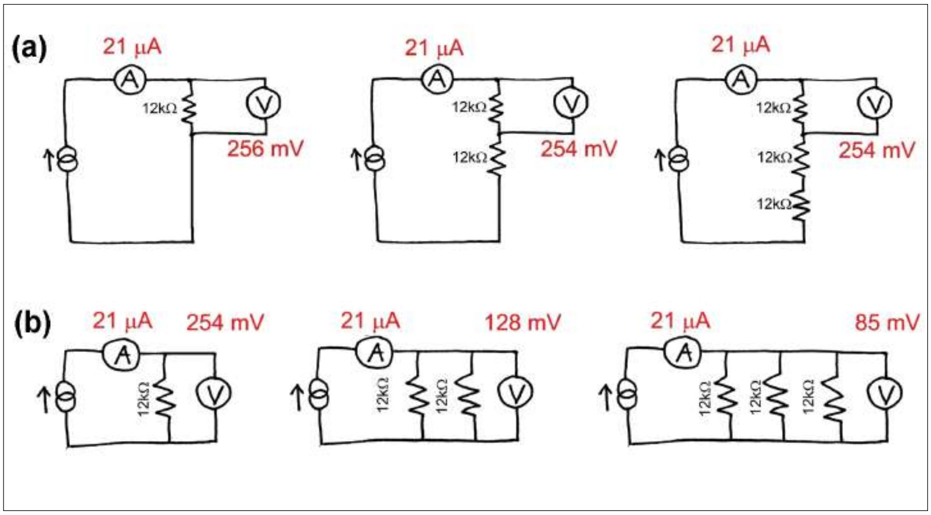

Fig. 3. Testing the idea that an LED works as a source of constant current using the two-LED unit as a power source (we used a symbol that is normally used for constant current source in electronics). (a) Adding resistors in series: current driven by the LED source stays constant and therefore the voltage across an individual resistor remains constant too; (b) adding resistors in parallel: current driven by the LED source stays constant and therefore the voltage created by the source decreases as more resistors are added in parallel. Note that all resistors have resistance of 12 kΩ.

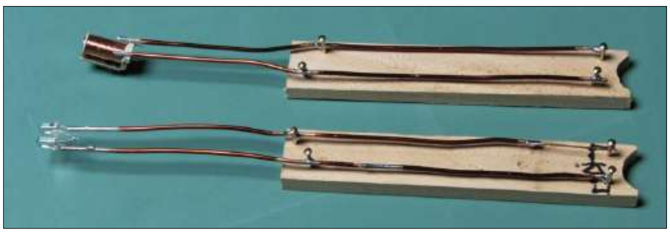

Fig. 4. A copper coil probe (above) and a two-LED probe (below).

such a current source to a circuit, the voltage across it adjusts to keep the current constant as long as the voltage is below the turn-on voltage, which is determined by the energy gap [about 1.7 V for yellow LED, see graph in Fig. 2(c)].

Now it is a good time to ask the students to explain how a regular battery works as an almost constant voltage source, more precisely a constant emf source. Encourage them to think of emf as a work per unit charge that the battery produces through chemical reactions. Since the energy per reaction is a property of the reaction itself and not how many reactions you run in parallel, the amount of work that the battery produces per each group of electrons passing through the battery should be constant, i.e., constant energy per charge. The number of electrons passing through the battery per unit time though should depend on the internal resistance of the battery and external resistance of the load.

We suggest using these activities in an atomic physics unit, where students learn the microscopic nature of the LEDs. Such timing will allow your students to come back to dc circuits one more time, to refresh their memory and to deepen their understanding of electric circuits.

Temperature dependence of different devices

In our traditional curriculum students learn that the temperature affects the resistance of metals. Here we will extend the investigation of the temperature dependence of the resistivity of materials such as semiconductors and specifically p-n junctions. We assume that the students are familiar with LEDs and their *I-V* curves through activities described in Ref. 2.

Equipment: Styrofoam cups, liquid nitrogen, hot water; a copper coil probe (a small coil from ordinary relay, room temperature resistance 58 Ω, soldered to long rigid connecting wires); a two-LED probe (two yellow LEDs[5] in series soldered to long rigid connecting wires), see both in Fig. 4; and a spectrometer.[8]

Students working in groups perform the following activities.

1. ***Observational experiment:*** Connect the copper coil probe to a 4.5-V battery (we used three 1.5-V batteries) and an ammeter in series and measure the current through the coil at room temperature, at the temperature of hot water, and at the temperature of liquid nitrogen. Then repeat the same measurements with the LED probe directly connected to the 4.5-V battery. We suggest for safety reasons that the teacher perform the experiments or show the videos.[9]
2. ***Patterns:*** Record the patterns in the ammeter reading when both probes are at different temperatures as well as any changes in the brightness or color of the LED probe.
3. ***Testing experiments:*** Design and conduct experiments to test the patterns.
4. ***Explanations:*** Explain the observed patterns.

In the observational experiment, students might obtain the results similar to those in Table I and in Fig. 5.

There are three patterns that emerge from observations: changes in current, changes in color, and changes in brightness. We suggest that you encourage the students to address them one by one.

• ***Current patterns:*** The current through the LED probe decreases with temperature until it drops to zero. This decrease in the current to zero might lead the students to the idea that the properties of the LED change with temperature, specifically, that the resistance of the LED increases when the temperature decreases. Another explanation can be that the turn-on voltage increases. Both explanations can be used to

Table I. Current through the probes at different temperatures and observations of LED color. The coil and the LED probe were connected to a 4.5-V battery.

Temperature	Current through the copper coil probe	Current through the LED probe	Comments
Room temperature (22 °C)	72 mA	26 mA	The LEDs glow yellow.
Boiling water (93 °C)	58 mA	36 mA	The color of the LEDs changes from yellow to orange.
Liquid nitrogen temperature (-196 °C)	470 mA	< 1μA (steady decrease from room temp. value)	The color of the LEDs changes from yellow to green.* At first the LEDs glow brighter but then dimmer and dimmer until they stop glowing.

*LEDs of other colors also exhibit such blue shift when cooled in liquid nitrogen. In our case we found that the yellow LEDs produce the most dramatic change in color.

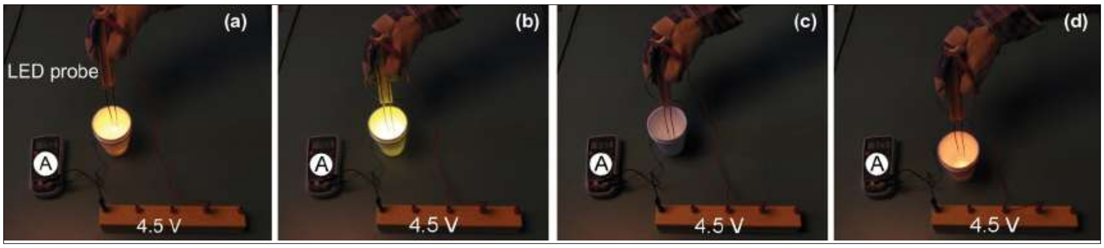

Fig. 5. The color of yellow LED depends on the temperature: (a) At room temperature it glows yellow (photo shows LED just before it was immersed in liquid nitrogen); (b) When it is cooled down, the color gradually changes to green; (c) When the LED temperature approaches the temperature of liquid nitrogen, it glows dimmer and dimmer until it turns off. When the same LED is immersed in boiling water, it emits orange light. In all cases the LED probe was connected in series with an ammeter and 4.5-V voltage source. Note that the person who is performing the experiments is wearing protective gloves.

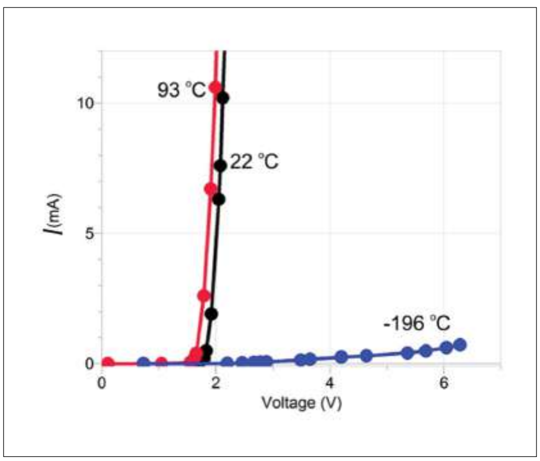

Fig. 6. The *I-V* curve for a yellow LED at three different temperatures. Note the slight change in turn-on voltage and the dramatic change in the steepness of the curve after cooling.[10] Error bars are about the size of the dots on the graph.

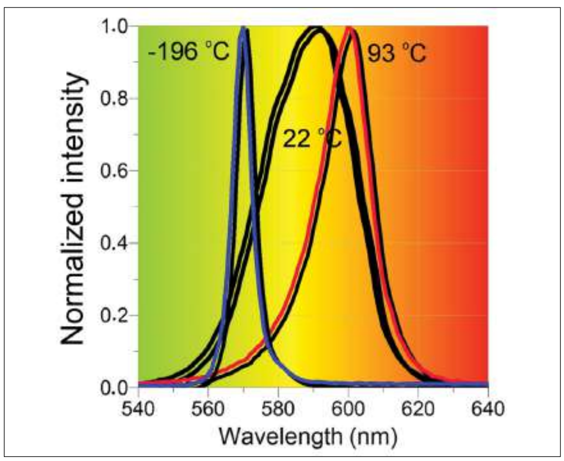

Fig. 7. Spectra of yellow LED at three different temperatures. Peak values of wavelengths are 570 nm, 590 nm, and 600 nm.[8]

make predictions about the outcome of the experiment in which students collect the *I-V* curve data for the LED when it is submerged in liquid nitrogen. The former explanation predicts a decrease in the slope of the curve, and the latter predicts an increase in the turn-on voltage compared to the room temperature. The opposite changes are predicted when the LED probe is submerged into boiling water. However, we expect these changes to be much smaller as the temperature difference is smaller (71 °C compared to 218 °C).

For *I-V* curve measurements we used a single yellow LED directly connected to a variable voltage source. The same measurements can be made by using a 9-V battery and a potential divider (see Ref. 2). The results from these measurements are shown in Fig. 6. The lower the temperature, the less steep the *I-V* curve is, which means that the resistance (strictly speaking, differential resistance) of the LED increases as the temperature decreases. The same graph also shows that the turn-on voltage slightly increases with decreasing temperature, but the effect is much smaller than the change in the slope of the curves. Using the *I-V* curve students should be able to infer that the increase in resistance is the dominant effect responsible for the observed decrease in current through the LED. Students might be able to explain the changes in resistance of the LED if they are familiar with their microscopic structure: at lower temperatures the number of charge carriers (free electrons and holes) decreases. The change in the turn-on voltage is more complicated and is related to the second pattern, discussed below.

• *Color patterns:* The color of the LED changes with temperature, specifically lowering the temperature leads to a color shift toward shorter wavelengths. The students might remember that the turn-on voltage is related to the color of the LED, thus this pattern should not be surprising. They can test the pattern by measuring the spectra of the LEDs at different temperatures using a spectrometer. The measurements of spectra that are consistent with the visual observations of the LED colors should show that the peak wavelength decreases when the LED is cooled. This is exactly what happens when we conduct the experiment (Fig. 7). The measurements in Fig. 7 were done with the two-LED probe and the spectrometer with an optical fiber. To make the two-LED probe glow in liquid nitrogen, we increased the voltage to about 12 V. When you do this make sure you decrease the voltage before you remove the LEDs from the liquid nitrogen; otherwise, the LEDs will burn out!

While we expect that the students can come up with the explanations of the changes of resistivity, we think that the explanations of the changes in the turn-on voltage and, consequently, the color are beyond high school and even college students. We provide the explanations for the teachers and we suggest that they share those with the students if students express "the need to know."

When the LED is cooled down, distances between the atoms in the semiconductor shrink, resulting in slightly increased overlap of electron orbitals.[11] This raises the energy gap of the semiconductor,[12] which in turn results in the larger energy of the emitted photons (shorter wavelength). The energy gap change is on the order of the thermal energy change (approximately a few 0.01 eV for cooling with liquid nitrogen). Heating the LED produces the opposite effect.

- ***Brightness patterns:*** The observations show that the intensity of the light emitted by an LED immersed in liquid nitrogen first increases and then decreases. The decrease of the intensity is easy to explain with the decrease in current and constancy of voltage. But why the initial increase? It does not make sense as the current decreases and the voltage stays constant. It would be excellent if students could see these conflicting pieces of data as a sign that the process of light production in LEDs by the recombination of electrons and holes is not straightforward. Then you can discuss with them that at any temperature the light producing recombination of electron-hole pairs competes with the non-radiative recombination processes that produce thermal energy through lattice vibrations (phonons). At lower temperatures the lattice vibrations are less pronounced, and therefore more electron-hole pairs emit photons instead of taking the non-radiative path of recombination through vibrations. This leads to enhancements of the light-producing processes.[9,13]

Using LEDs to broaden student learning of physics beyond traditionally taught physics concepts: Fluorescence

This sequence of activities will prepare students to learn about fluorescence. The subject of the investigations is a white LED.[14,15] Students should be familiar with photons, spectral analysis, with the basic rules for additive color mixing, basics of LEDs (such as *I-V* curve and the fact that LEDs emit approximately monochromatic light), and the *I-V* curve for an incandescent light bulb.

Equipment: LEDs: red, green, blue, and white; diffraction grating, voltmeter, ammeter, DC voltage source, white paper, fluorescent markers, and regular (non-fluorescent) markers.

Students working in groups perform the following activities.

1. ***Observational experiments:*** Observe the spectra of blue, green, and red LEDs using a grating. What are the similarities and the differences between the spectra? Now observe the spectrum of a white LED.
2. ***Patterns and explanations:*** Describe the similarities and the differences between the spectra of blue, green, red LEDs, and the white LED. Propose several mechanisms that explain the spectrum of the white LED.
3. ***Testing experiments:*** Design and perform experiments to test the explanations that you devised in part 2. Make predictions about the outcomes of the testing experiments using each explanation. After you finished the experiments and compared the outcomes to the predictions, decide what mechanism was not ruled out.

Fig. 8. Spectra of different LEDs as seen through the grating with 500 lines/mm: a) red, green, and blue LED spectra; b) white LED spectrum.

Students should observe that the colored LEDs have narrow band-like spectra [Fig. 8(a)] while the white LED spectrum covers a wide range of wavelengths [Fig. 8(b)].

Below we show three explanations that might be suggested by the students. Explanations 1 and 2 are most common as they are based on students' previous knowledge. If the students do not come up with explanation 3, we suggest that the teacher triggers this explanation.

- ***Explanation 1:*** This explanation is usually suggested first: inside the white LED there are small red, green, and blue LEDs connected together[15] (if the students are not familiar with additive color mixing you can use the LED color mixer to help them devise these rules[17]). Ask the students to suggest how these LEDs might be connected (in series or in parallel).
- ***Explanation 2:*** The white "LED" does not use the LED mechanism to glow but instead has an ordinary incandescent light bulb inside that emits white light.
- ***Explanation 3:*** The white LED is made of a single color LED that is covered with a layer of some special material that changes the color of light when the LED light passes

through it. Our eyes perceive the resultant light emitted by such a device as white.

To test the proposed explanations, the students might suggest collecting the *I-V* curve data for the white LED. The predictions of the outcomes of the experiments based on each of the three different explanations that they need to make before conducting the experiments are as follows:

– *If* explanation 1 that the white LED consists of a red, green, and blue LED is correct, *and* we measure the *I-V* curve of the white LED, *then* the turn-on voltage of the white LED should be at least about 6V (the sum of the three turn-on voltages, assuming series connection) or about 1.5 V (the turn-on voltage of the red LED, assuming parallel connection).

– *If* explanation 2 that inside the white LED is an incandescent light bulb is correct *and* we collect the current and voltage data, *then I-V* curve of the white LED should resemble the *I-V* curve of an incandescent light bulb [a non-zero current for any $\Delta V \neq 0$, the slope of the curve decreases with increasing voltage, and the *I-V* curve is symmetrical: $I(-V) = -I(V)$].

– *If* explanation 3 that there is a single color LED inside the white LED is correct, *then* the *I-V* curve should resemble the *I-V* curve of one of the color LEDs.

The outcome of the experiment is shown in Fig. 9: the white LED has the *I-V* characteristic that is very similar to that of the blue LED (students should realize that the turn-on voltage is the only parameter of the *I-V* curve that reliably corresponds to the color of the LED).

This outcome rejects explanations 1 and 2 and leaves explanation 3 as the only explanation that has not been rejected. If the students learned how to observe an LED with a microscope (see ref. 2), they might propose another testing experiment, to explore the interior structure of the white LED and to compare it to the structure of the blue LED. If the explanation 3 is correct, then in the white LED they should see similar structure to the blue LEDs but covered with some kind of material. The results (Fig. 10) agree with the idea that

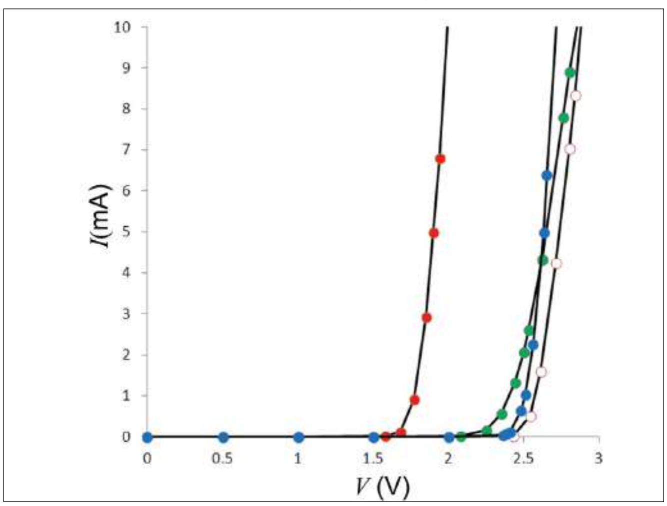

Fig. 9. *I-V* curves for red, green, blue, and white LEDs[7] (dot colors correspond to the colors of the LEDs). Note that the turn-on voltages of the white and blue LEDs are almost equal. Error bars are about the size of the dots on the graph.

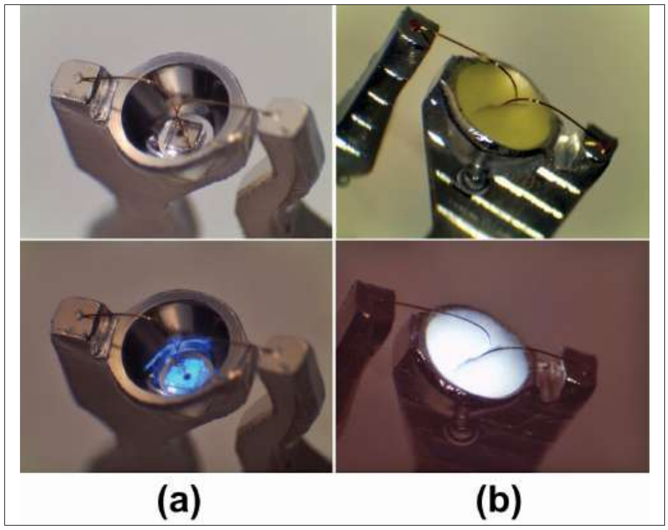

Fig. 10. Blue (a) and white (b) LEDs under a microscope when switched off (top) and on (bottom). Note that these LEDs employ geometry of the p-n junction where both leads are connected at the top.

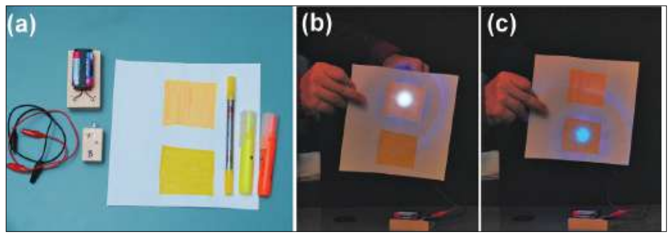

Fig. 11. The final testing experiment of the explanation on how the white LED works: (a) equipment (3-V battery source, blue LED, wires, and different markers (regular and fluorescent); (b) blue light passing through the white paper colored with a fluorescent marker and (c) through the paper colored with a regular marker.

white LED is constructed by covering blue LED p-n junction with a layer of yellowish material.

The students can run an additional experiment to test this explanation. Let them make paper color filters of different yellow shades by coloring white paper with different regular and fluorescent markers (we used yellow and orange markers).[18] Before conducting the experiments, the students should predict what they will see when they cover the blue LED with the yellow paper. *If* the explanation 3 is correct *and* you cover the blue LED with a yellow paper, *then* the yellow colored spot on the paper should appear white. The setup is shown in Fig. 11(a). The outcomes of the experiments [Fig. 11(b) and (c)] show that the prediction matches the outcome only for a certain kind of yellow marker. The students can now conduct a new observational experiment in which they repeat the experiment described above using red and green LEDs. They will find out that the colors of these LEDs remain unchanged even when light passes through the paper colored with a fluorescent marker. At this point students will want to know why some yellow markers produce white light only when a blue light is passed through and the other colors do not. They are ready to learn about fluorescence.

Summary

The goals of this paper were to show that by using the physics knowledge of how an LED functions, we could help our students deepen their understanding of batteries, other sources of electric energy, and the temperature dependence of resistivity of different materials. We also showed how using this same knowledge, students could learn about the phenomenon of fluorescence. The phenomenon of fluorescence in addition to the invention of a blue LED enabled the design of a white LED, which now is replacing an incandescent bulb all over the world. The importance of the discovery of a blue LED was recognized in 2014 with a Nobel Prize awarded to its inventors, Isamu Akasaki, Hiroshi Amano, and Shuji Nakamura.

Acknowledgments

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References

1. Gorazd Planinšič and Eugenia Etkina, "Light-emitting diodes: A hidden treasure," *Phys. Teach.* **52**, 94–99 (Feb. 2014).
2. Eugenia Etkina and Gorazd Planinšič, "Light-emitting diodes: Exploration of underlying physics," *Phys. Teach*. **52**, 212–218 (April 2014).
3. E. Etkina and A. Van Heuvelen. "Investigative Science Learning Environment – A Science Process Approach to Learning Physics," in *Research Based Reform of University Physics,* edited by E. F. Redish and P. Cooney (AAPT, 2007), online at http://per-central.org/per_reviews/media/volume1/ISLE-2007.pdf.
4. Eugenia Etkina, Alan Van Heuvelen, David T. Brookes, and David Mills, "Role of experiments in physics instruction – A process approach," *Phys. Teach.* **40**, 351–355 (Sept. 2002).
5. Lillian C. McDermott and Peter S. Shaffer, "Research as a guide for curriculum development: An example from introductory electricity. Part I: Investigation of student understanding," *Am. J. Phys.* **60**, 994–1003 (Nov. 1992) and Paula Vetter Engelhardt and Robert J. Beichner, "Students' understanding of direct current resistive electrical circuits," *Am. J. Phys*. **72**, 98–115 (Jan. 2004).
6. The following are just examples of curriculum materials relevant to this issue: Peter S. Shaffer and Lillian C. McDermott, "Research as a guide for curriculum development: An example from introductory electricity. Part II: Design of instructional strategies," *Am. J. Phys*. **60**, 1003–1013 (Nov. 1992); A. B. Arons, *A Guide to Introductory Physics Teaching* (Wiley, New York, 1990).
7. In our experiments we used the following OptoSupply LEDs: red OSHR511P, yellow OS5YKA511P, green OSPG511P, blue OSUB511P, and white OSPW511P.
8. We used a Vernier emissions spectrometer.
9. The videos of the experiments are available at http://youtu.be/E87ovkzTxUo and http://youtu.be/oPWcczSgxRE.
10. Note: if we increased the voltage across the yellow LED cooled in liquid nitrogen above about 6 V, it suddenly flashed bright and burned due to voltage breakdown.
11. George C. Lisensky, Rona Penn, Margaret J. Geselbracht, and Arthur B. Ellis, "Periodic properties in a family of common semiconductors – Experiments with LEDs," *J. Chem. Educ*. **69**, 151–156 (Feb. 1992).
12. See Charles Kittel, *Introduction to Solid State Physics*, 3rd ed. (Wiley, 1967), p. 306, footnote.
13. Notice that we used two yellow LEDs in series directly connected to the voltage source (4.5-V batteries). The goal of such arrangement is to keep constant voltage across the LED and thus help students see the pattern clearly. If the LED is connected to the voltage source in series with a resistor, the voltage across the LED will increase as the LED's temperature decreases. In this case it might happen that the LED will remain glowing brighter when immersed in liquid nitrogen, although the current through the LED will decrease.
14. A similar sequence of activities called Great White LED, has been developed at Kansas State University as a part of Visual Quantum Mechanics material, http://web.phys.ksu.edu/vqm/VQMNextGen/App&ModelBuilding/greatwhiteled.pdf. GWL combines *I-V* curves and spectral measurements with computer simulations to gradually construct an explanation about how white LED works. Our approach is different as we use only experiments, provide more activities (original), and systematically follow the ISLE cycle.
15. The activities described in this section can be done also with a magenta LED (sometimes called a pink LED). A magenta LED consists of a blue LED covered with a reddish fluorescent layer.
16. Note that such white LEDs did exist for short time in the 1990s. However, instead of being wired internally these LEDs had external leads for each of the LEDs.
17. Gorazd Planinšič, "Color mixer for every student," *Phys. Teach.* **42**, 138–142 (March 2004)
18. Demonstrations of the white LED principle using blue LEDs and fluorescent markers have been described before in Masahiro Kamata and Ai Matsunaga, "Optical experiments using mini-torches with red, green and blue light emitting diodes", *Phys. Educ.* **42**, 572–578 (June 2007).

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