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PLS Torino: A way to discover semiconductors in a school lab

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Summary. — In the wide range of PLS activities, one on semiconductors was realized with high-school 4th- and 5th-year students. After an introduction on semiconductor and electromagnetic radiation concepts, students assembled circuits, observed photoresistor and LED behavior and compared experimental and theoretical results. We especially paid attention to energy conversions and devices applications. An important point of the project is that it can be easily realized in our schools because low-cost devices are used. Moreover, discussing experimental results, it is possible to correct or complete students phenomena interpretation.

PACS `01.40.ek` – Secondary school.
PACS `01.40.gb` – Teaching methods and strategies.

1. – Why scientific education? Why academic orientation?

There are many reasons for studying semiconductors with students. As we know, these materials had and still have a very important impact in everyday life. But, actually, what can really impress students is trying to watch something very small. We are approaching "microscopic physics" and we need to "imagine", starting from macroscopic evidences. I cannot see electron-hole production, but I can see its effects. So, what has always fascinated physicists can attract students, too, or at least the future physicists. Other answers to these questions will be surely found in the method we used.

2. – The method

The project has been realized together with high-school 4th- and 5th-year students, in their own school laboratory. This was possible because power supply, voltmeter, ammeter, cables and resistances are commonly used at school and low-cost semiconductor devices are available. Photoresistors and LEDs have been used. The project is based on:

- team work;
- learning by doing;
- questions.

Fig. 1. – Photoresistor (grey: conductor; dark grey: semiconductor).

Since classes were quite numerous, some stationings were prepared, as many as the working groups. Team work has been fundamental in this project: each team (composed by 4–5 students) had to be independent during measurements. Indeed, after a first theoretical introduction and briefing about targets, a form with some simple hint and questions has been given to students. In this way they had to think about and face different issues about measurements and physics. There was the possibility to ask the tutor for help, of course, but, first, the work groups had to find their own solution. There are at least two reasons for this choice: giving students time to understand what they are doing (learning time is different for each one) and because doing is a more effective learning method than listening. We would like to underline the importance of questions in this project. Does my model agree with experimental results? What is the meaning of my results? What can I do to verify or reject my theory? Questions should help students to be aware of what they are doing and to get an idea on processes consistent with reality. After team work, time to share results and considerations with the all class was done. This has been done for each device.

3. – Photoresistor

Photoresistor is a light sensible device, composed by two metal combs joined by a semiconductor (fig. 1). In this device, electric resistance decreases with increasing lighting. This is related to the increasing number of free carriers generated by photon absorption in the semiconductor material if the photon energy is close to or bigger than the gap energy (figs. 2(a) and (b)). If the voltage supply is on, free carriers can move in the semiconductor and we measure the current (fig. 2(c)).

How to approach this device? Once students have built a circuit to measure voltage and current in the photoresistor, they need time to verify what they know from theory. We started lighting the photoresistor with a common incandescent lamp. What happens by fixing lamp-device distance (that is fixing lighting)? If you are still lighting, why do not you see current increasing? How can I verify or reject my theory? These questions let students think about carriers kinetic energy dispersion and electron-hole annihilation and about generation-annihilation equilibrium, that is why current is constant in instruments sensibility.

Once a student said that the current was constant because all valence electrons were already been excited to the Conduction Band (CB). Another one answered that if it was true, approaching the lamp to photoresistor, you could not see current increasing. He said that it was because joule effect and because the e-h annihilations number is

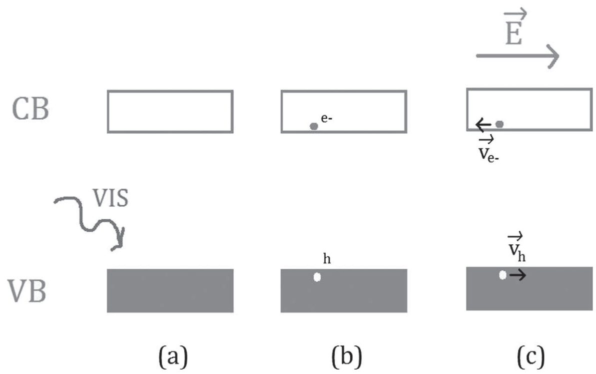

Fig. 2. – Simplified processes in a photoresistor: (a) photon absorption, (b) electron-hole pairs production, (c) effects of an external electric field. CB stands for Conduction Band, VB stands for Valence Band, E stands for the electric field, VIS stands for a photon in the visible range.

equal to their production number. We reached our goal: they thought about physics, starting from evidences and they applied their previous knowledge. If students have not understood the process yet, there is another useful question. How much time does photoresistor take to respond to illumination variation? Observing very short intervals, you can believe that annihilation rate can be close to production rate, that is why quickly current decreases.

Let us go beyond and let us measure tension and current in the photoresistor before and after approaching: in the closest position photoresistor is dissipating more energy. Where does this energy come from? Since now the photoresistor is closer, usually some students said that it comes from the lamp: more photons, more current. Actually, more photons means more electrons in the Valence Band (VB) only, less resistivity and (keeping voltage constant) more current, that is more energy. Power unit has to supply more energy to keep set up voltage constant. That is a common feature of power unit rather strange for students if they think about it. So, let us think about our houses electrical grid: turning on appliances, we do not see power variation in home's lamps. Another way to see constant voltage, while electrical load is changing, is using a battery and two light bulbs. At first let us observe a one bulb circuit, then a two bulbs series circuit and a two bulbs parallel circuit. The single and series bulbs get the same voltage, current and energy, that we see as same illumination. These qualitative observations show how current, tension and power can vary. As we can see, we are now working on power unit, while photoresistor cannot supply energy, resistance can be varied, only: photoresistor is a detector. Are students still not aware of it? Turn off power unit!

Well, now we wonder if there are quantitative observations able to verify our theoretical model, in which an absorbed photon produces a free electron-hole pair. Consider the number of photon inciding on photoresistor in the time unit when the lamp is on (N^p_{on}) and off (N^p_{off}) and the number of free electrons in the time unit in the two situations (N^e_{on}, N^e_{off}). It is possible to calculate the variation in the number of photons inciding on photoresistor and in the free electrons number, for on/off lamp ($\Delta N^e = N^e_{\mathrm{on}} - N^e_{\mathrm{off}}$, $\Delta N^p = N^p_{\mathrm{on}} - N^p_{\mathrm{off}}$). For our target, on/off variations in electron and photon numbers are compatible with the model if they are of the same order of magnitude. Let us fix the distance between the lamp and the device at the value d. To calculate ΔN^p, we evaluate the lamp power P_{lamp}, its efficiency factor (ϵ) and the medium photon energy E. We considered that photoresistor can absorbe visible light and that the luminous efficiency factor of incandescent lamp is 20%. To calculate the medium energy E_m of inciding photons, we give students an incandescent lamp spectrum and in the visible range they opted "by eye" for 650 nm as medium value ($E_m = 3 \cdot 10^{-19} J$),

$$\Delta N_t^p = \frac{P_{\text{lamp}} \cdot \epsilon}{E_m}.$$

These photons distribute isotropically and after the time d/c, they are distributed on a d radius spherical surface (where c is the light speed). In this way, only a small part of electrons (ΔN^p) reaches photoresistor surface (S):

$$\Delta N^p : \Delta N_t^p = S : 4\Pi d^2.$$

You can calculate ΔN^e, measuring the current difference for on/off lamp.

$$\Delta N^e = \frac{\Delta I}{q}.$$

At the distance $d = 40$ cm, we got $9 \cdot 10^{15}$ electrons/s and $2 \cdot 10^{15}$ photons/s.

In conclusion, it is important to make students aware that a trend proportional to $1/d^2$ is quite common in nature. The visual impact we got with a photoresistor's circuit and representing I(d^2) can be recalled in many others situations.

4. – LED

We now switch to another semiconductor device: the Light-Emitting Diode. A LED works as an open circuit if it is inversely polarized, and as a light emitter if forward polarized. In this second function, electrical energy is transformed in luminous energy. We said to students that the voltage can supply electrons enough energy to jump to the conduction band and that "enough" means more or less equal to device energy gap, that is characteristic of the material. We called V_0 this threshold voltage, such as

$$eV_0 = E_{\text{gap}}.$$

How does light emission happen? Electrons and holes can recombine with light emission and the emitted photon has an energy close to E_{gap}:

$$h\nu = E_{\text{gap}}.$$

In this way it is possible to understand how photon frequency depends on the material and that:

$$eV_0 = h\nu.$$

In table I, wavelength and expected threshold voltage have been written for the used LED.

In the first experimental part we proposed students to verify the different behavior for forward and inverse bias. They measured I and V starting from -3 V, with 0.5 V steps,

TABLE I. – *Expected and experimental threshold voltage for different colors.*

	Emitted λ [nm]	Expected V_0 [V]	P LED V_0 [V]	WCP LED V_0 [V]
Blue	450–475	2.76–2.61	1.8 ± 0.1	2.5 ± 0.1
Green	495–570	2.50–2.17	1.8 ± 0.1	2.1 ± 0.1
Red	620–750	2.00–1.65	1.8 ± 0.1	1.6 ± 0.1

until typical forward voltage (Red: 1.9 V; Blue: 3.5 V). Can we understand the LED behavior with this curve? Shall we need shorter steps to describe transition's region? What does the I-V curve look like?

In the second part we want to test a qualitative method to find V_0, that has to be compatible with E_{gap}. It consist in observing when LED turns on and writing the corrisponding voltage. This method can lead to different considerations about human body as first measurement instrument and about results we are going to discuss. We first measured V_0 for type P LED, where P means colored plastic, and we obtained 1.8 V for all the LEDs, that is quite different from expected values.

As we can imagine, first students reaction (at least of some of them) was to modify results to get correct results. What is a correct result for an experiment? Let us start accepting experimental results and trying to understand them. Trusting in our measurements we supposed that all the LEDs are actually made of the same semiconductor, that is why they turn on at the same voltage, they could be white LED and the color we see could be selected from the white spectra by the colored plastic. Is it true? Hard to demonstrate.

We decided to test another kind of LED, let us call it type WCP (water clear plastic) and we obtained different results (table I). Are this V_0 measurements compatible with the expected values? The results are a little bit smaller than expected. We though that there is a certain probability that few electrons can exceed the potential difference for applied voltage less than E_{gap}/e. This is coherent with I-V characteristic curve, in which we can observe a slowly increasing current for $V < E_{\text{gap}}/e$. We also tough that our eye can see a really small number of photons, that makes it a very sensitive instrument.

We concluded that the voltage measured by eye its an underestimation of V_0, but still a good approximation. About nature of P type LED we could not confirm our hypothesis. For sure this gives the idea for another activity: giving students home made painted LED with white emission. They should obtain the same V_0 and think about what really give the perceived color.