RASPBERRY SOLAR CELL, A VERSATILE TOOL IN TEACHING PHYSICS

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ABSTRACT

The article describes the realization and teaching application of the raspberry solar cell. We present its components and the electron transports of the raspberry solar cell. The description uses the same four steps, the excitation, the charge separation, the diffusion and the regeneration, as the single n-p junction solar cell, and as the light-dependent reactions of photosynthesis. To strengthen the similarities between these solar energy converters, we underline analogies in energy levels and bands. These analogies offer an interdisciplinary approach in teaching applications. The real situation, the construction of the raspberry solar cell, allows the science teacher to place the notion of energy and the solar energy conversion into an interdisciplinary context. For this reason, we organized student activities around this versatile tool. Here we expose the results of a test, realized by homemade solar cells, sensitized by three organic dyes, exposed to different light sources.

RASPBERRY SOLAR CELL

A raspberry solar cell is a dye-sensitized solar cell composed of an anode, a cathode and an electrolyte. The construction of a raspberry solar cell is an interesting project work, but it requires special coated glass plates, laboratory materials, special equipment and preparations for the physics teacher. See needed materials and steps to follow with more references in [1].

The anode consists of a transparent glass plate covered by a semi-conductor layer (Fluorine doped Tin-Oxide or FTO). On this plate, we stabilized a porous, wide bandgap semiconductor (titanium-dioxide or TiO_2) layer. According to its wide bandgap, the semiconductor layers are insensitive to visible light. To prepare a light-sensitive anode, we fixed raspberry dyes (anthocyanin molecules) on the TiO_2 layer. On one hand, this combination of semiconductor layers and raspberry dye layer allows increasing the effective surface of solar cell. On the other hand, the difference between the conduction bands of FTO and of TiO_2 results electrons on the FTO glass plate. The energy of the captured photons excites the electrons (of anthocyanin molecules), which follow the energetically suitable way to the FTO layer.

As cathode, we used another transparent FTO coated glass plate, covered with a carbon layer. This layer acts as a photo-reflecting layer and a catalyst of the electrolyte regeneration. Between these two electrodes, a regenerative electrolyte (iodide/tri-iodide) solution closes the circuit. The solar cell is ready to convert the photon’s energy [2].

The left panel of Fig.1. shows the simplified structure of a raspberry solar cell. The right panel presents a homemade raspberry solar cell. The anode side is beige, because TiO_2 is white, the raspberry juice is red, the electrolyte is brown and mixing these colours results in beige. The carbon on the cathode side is black.

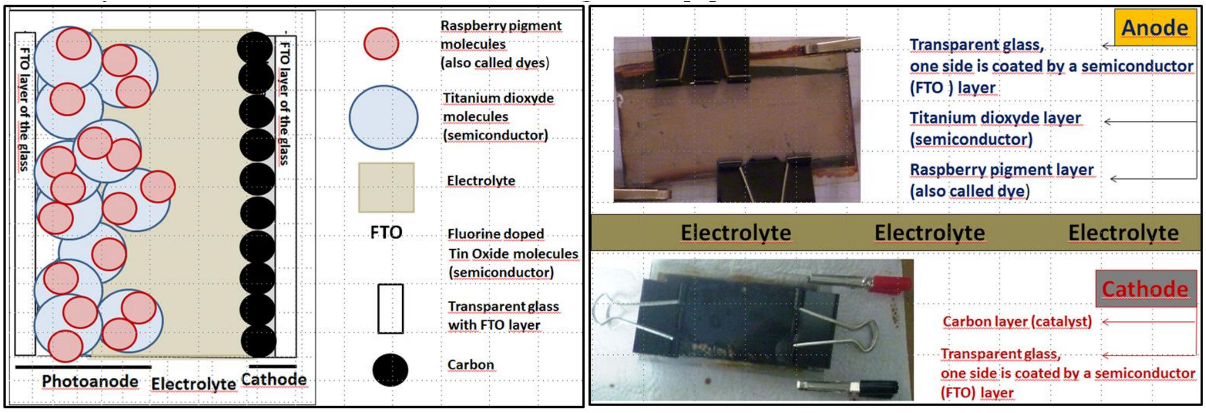


Fig.1. Structure of a raspberry solar cell. Components of a homemade raspberry solar cell

HOW IT WORKS

Due to the internal structure, the unit is a galvanic cell, and it works in dark as well. If we expose the anode side to light, first a ground state raspberry dye molecule absorbs a photon. The excited dye molecule injects an electron into the TiO_2 grain (crystal), at the point where the TiO_2 adsorbed the raspberry dye. This step is the charge separation. After that, the electrons diffuse to the FTO from the TiO_2 layer. Connecting a voltmeter between the electrodes, it measures a voltage. See the left panel of Fig.2.

If we connect the electrodes using an ammeter, it measures an electric current. The electron travels through the outer circle, reaches the cathode, and regenerates the electrolyte and the dye in two steps, as the right panel of Fig.2 shows [3].

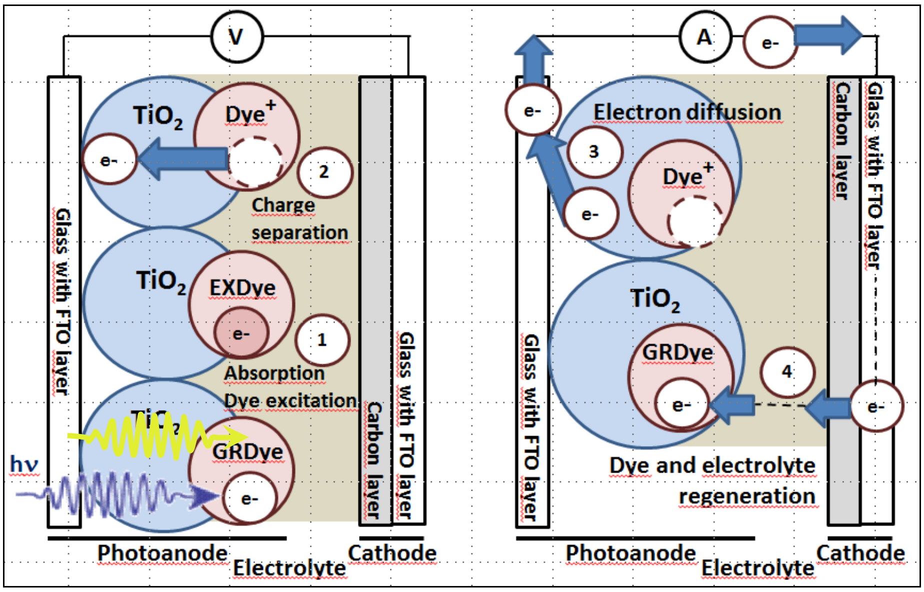


Fig.2. Photovoltaic effect   Electric current

One can follow the energy of an electron on the left panel of Fig.3, where we represent the relative energy levels and bands [4]. On the abscissa, there are the components of a cell in spatial order, starting with the place of the photon absorption (Dye). Here the excited state level (EX) is energetically the highest level. The four main steps of an electron-cycle are numbered on the figure. The right panel of Fig.3. represents the components as they are in space. The most absorbed photons, absorbed by the pair TiO_2 – raspberry dye, are the photons of 2.3 eV. See the main steps of an electron-cycle in Table 1 and [5].

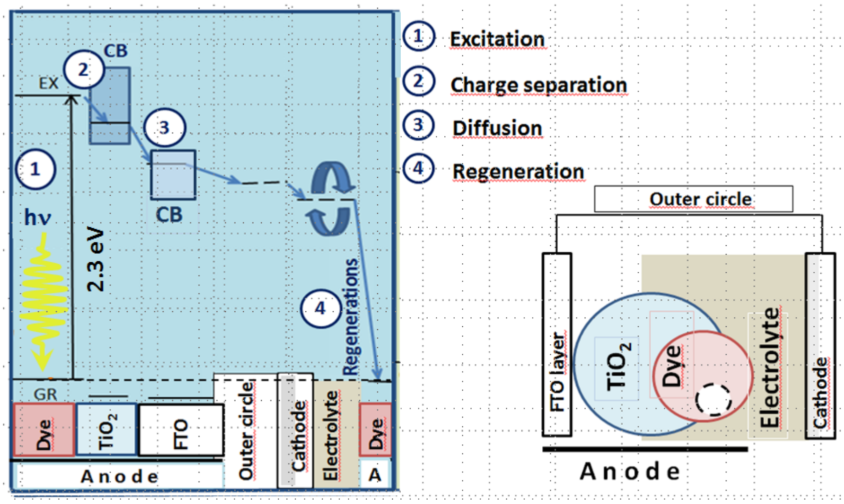


Fig.3. Raspberry solar cell: Relative energy levels and bands Actual order in space

Table 1. Main steps of an electron-cycle of the raspberry solar cell

Steps	Raspberry Solar Cell	
1	$GRDye + h \cdot \upsilon \rightarrow EXDye$	GRDye = ground state dye EXDye = excited state dye
2	$EXDye \rightarrow e^-_{TiO2,CB} + Dye^+$	I^- = iodide / I^-_3 = tri-iodide
3	$e^-_{TiO2,CB} \rightarrow e^-_{FTO,CB}$	$e^-_{TiO2,CB}$ = electron in the conduction band of TiO_2
4	Electrolyte: $I_3^- + 2e^- \rightarrow 3I^-$ Dye: $2\,Dye^+ + 3I^- \rightarrow 2GRDye + I_3$	$e^-_{FTO,CB}$ = electron in the conduction band of *FTO*

ANALOGIES AND SIMPLIFICATION I. – TEACHING SOLAR CELLS

In practice, most solar cells use semiconductors in the form of an n-p junction, which is formed by joining an n-type and a p-type semiconductor. Near the junction, in the depletion region, a photon's absorption results in an electron-hole pair. Both the electron and the hole can participate in conduction. After the diffusion to the n-type semiconductor, the electron travels through the outer circle and will recombine with a hole, which travels in the opposite direction and diffuse to the p-type semiconductor (see Fig.4.).

In a single n-p junction solar cell, an electron follows the same four main steps as in the raspberry solar cell. In the raspberry solar cell, the excitation and the charge separation steps are spatially divided, which simplifies the description. Here only the electron moves, because the positive dyes (Dye+) are adsorbed on the TiO_2 layer. These facts result in a simplified and localizable electron-cycle. Applying this analogy to the electron- and hole-cycle of a solar cell, the students can understand the basis of solar cells physics. See Fig.5. and Table 2.

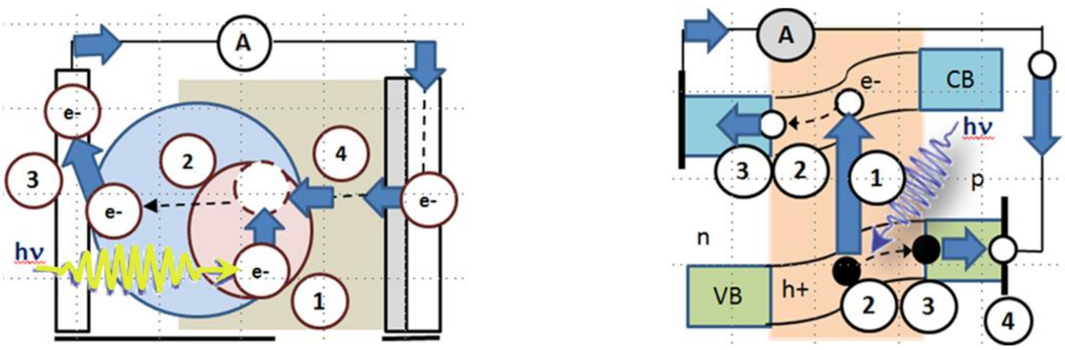


Fig.4. Raspberry solar cell: electron-cycle n-p junction solar cell: electron/ hole cycle

Table 2. Main steps of an electron-hole pair cycle of the n-p junction solar cell

Steps	n-p junction solar cell	
1	$e^-_{VB} + h \cdot \upsilon \rightarrow e^-_{CB}$	e^- = electron in the depletion
2	$e^-_{VB} + AC \rightarrow e^-_{CB} + h^+_{VB}$	h^+ = hole in the depletion; VB = valence band of depletion
3	e^-: Depletion→ n-typeSC_{CB}	CB = conduction band of depletion
	h^+: Depletion → p-typeSC_{VB}	AC = atomic core; SC = semiconductor
4	e^- / h^+ recombination: $e^-_{CB} + h^+_{VB} \rightarrow e^-_{VB} + AC^+_{VB}$	n /p = n- /p-type semiconductor

The comparison of the energy bands of the two types of solar cells shows that the raspberry solar cell has a simplified energy band structure because of the immobility of the dyes and of the localized steps of a cycle on the different components of the cell. On the n-p junction solar cell, the student has to follow the energy of the electron and of the hole, and has to understand the deformed energy structure of the depletion region, too.

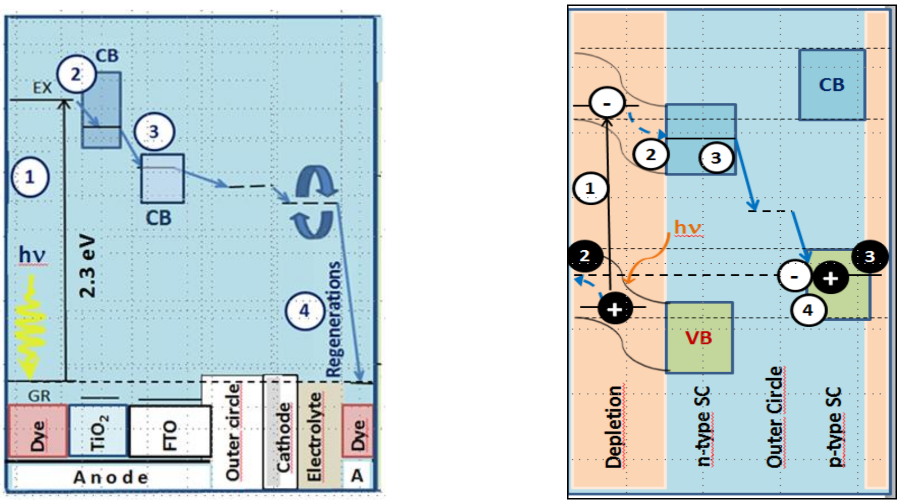


Fig.5 Raspberry solar cell: relative energy bands, n-p junction solar cell: relative energy bands

TEST OF A HOMEMADE RASPBERRY SOLAR CELL

After the realization, we used the raspberry solar cell as a galvanic cell, and we measured the voltage in dark. In use, the current supplied by the solar cells is important, and determines the electric power taken from them. We used different light sources (bulb, neon, halogen, LED, UV) and different dyes (raspberry-, blueberry- and mango dyes) to measure the generated current.

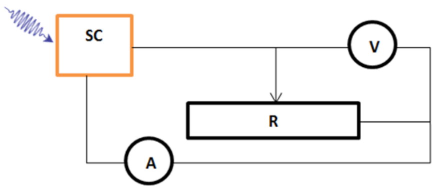
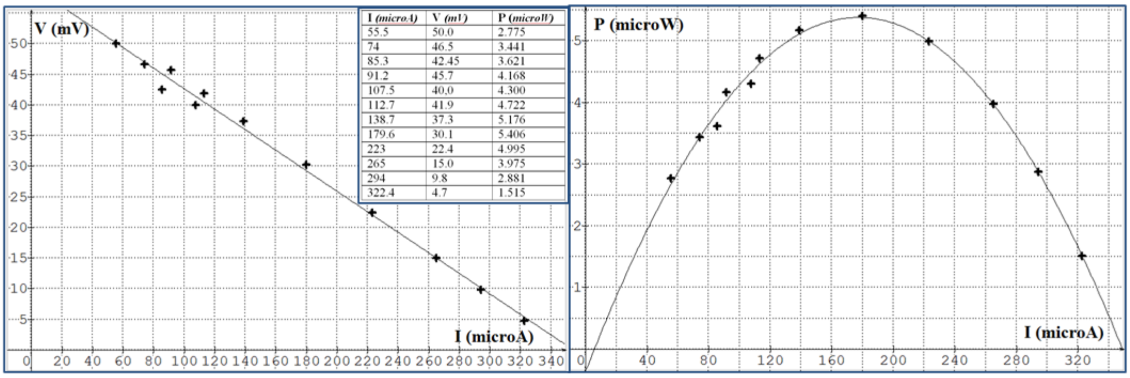


Fig.6. Solar cell as current source

For a comparative analysis of raspberry- and n-p junction solar cells, we used illuminated cells as current source in the electrical circuit of Fig.6, where we connected a variable resistor. We measured its voltage (V) and current (I) at same time. We found a linear dependence according to Ohm's law of the circuit ($V=V_0-R_{internal}\cdot I$), then we determined the internal resistances (R_i) and the electromotive forces (V_0) of the cells. For example, applying an UV light-source for raspberry cell, we measured a dependence V(mV)=60- 0.17·I(μA), by which

R_i=170 Ω, V_0=60 mV. For a commercial garden lamp, composed of n-p junction solar cells, we measured V(mV)=2471-307 I(mA), by which R_i=307 Ω, V_0=2471 mV.

We determined the maximal power output of the cells, on one hand using Ohm's law of the circuit ($P= (V_0-R_i \cdot I)\cdot I$), on the other hand analysing power-current functions. We defined the quotient $|P_{Ohm}-P_{function}| / P_{Ohm}$ as the relative power error. The test of the raspberry cell using an UV light-source, gives 7% optimal power relative errors. With the same light source, the relative power error for solar cell garden lamp was 12%. See Fig.7 and more test results in [6].



I (microA)	V (mV)	P (microW)
55.5	50.0	2.775
74	46.5	3.441
85.3	42.45	3.621
91.2	45.7	4.168
107.5	40.0	4.300
112.7	41.9	4.722
138.7	37.3	5.176
179.6	30.1	5.406
223	22.4	4.995
265	15.0	3.975
294	9.8	2.881
322.4	4.7	1.515

Voltage as function of current   Power as function of current

Fig.7. Solar cells as current source, illuminated by UV light-source

ANALOGIES AND SIMPLIFICATION II. - TEACHING PHOTOSYNTHESIS

The raspberry cell uses the same basic principle as plant photosynthesis to generate electricity from sunlight. Both processes require the absorption of the energy of photons. In the cycle of light dependent reactions of the photosynthesis, the electron follows the four main steps twice: excitation, charge separation, diffusion and regeneration.

The right panel of Fig.8 presents the absorptions of two photons of different frequencies, and that the linear electron transport chain connects the two parts of light dependent reactions, the photosystems I and II. Photolysis, the regeneration process in this case, with the electron replacement results in a cyclic operation.

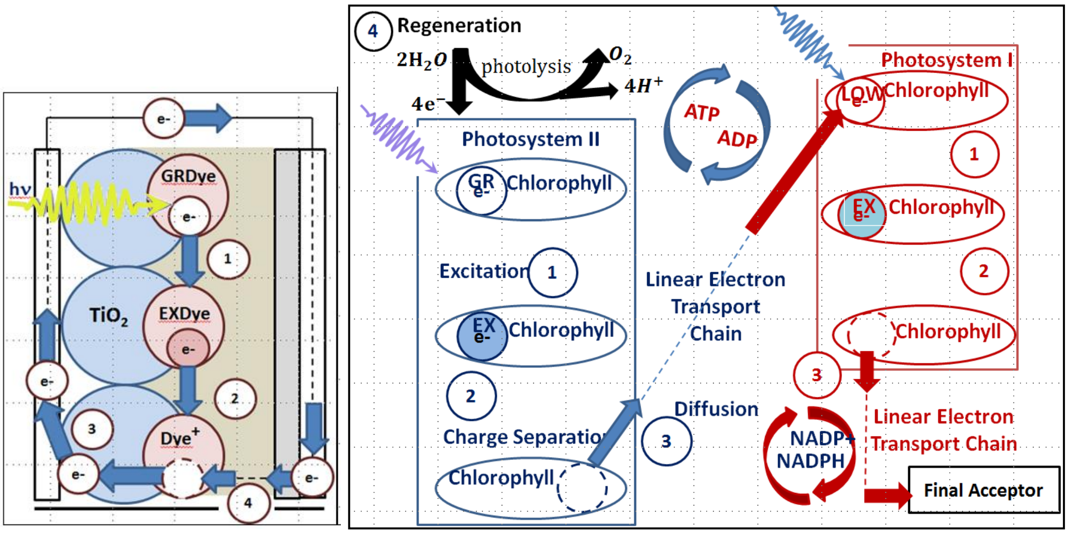


Fig.8. Electron-cycles: Raspberry cell   Light dependent reactions of photosynthesis

From the point of view of physics teaching, a comparative analysis of relative energy bands and levels underline the similarities of the two processes, in spite of the electron-cycle repeating twice. On Fig.9, we compared how different parts of a raspberry cell and of light dependent reactions use the energies of the photons. (For more details see [4], [5] and [7].)

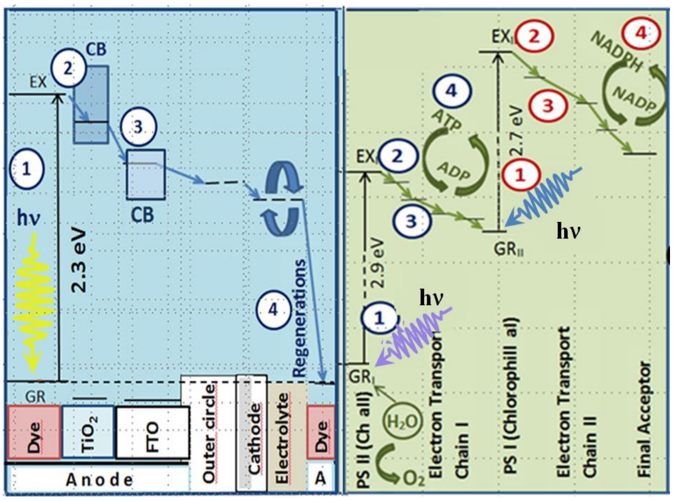


Fig.9. Raspberry cell: relative energy levels LDR of photosynthesis: relative energy levels

With the relatively simple energy cycle and energy band structure the raspberry cell can illustrate many different scientific subjects, like galvanic cells, semiconductors, n-p junction solar cells, light-dependent reactions of photosynthesis, current sources. Placing the energy concept into an interdisciplinary context can offer an understanding and integration of many different pre-existing concepts. It can help in the description of all types of solar energy converters, and in many issues of environmental sciences [8].

CONCLUSIONS

The raspberry solar cell works according to the same basic principle as other photovoltaic and galvanic systems. Based on this fact, physics curriculum and teaching objectives can utilize this analogy during physics teaching at several levels. We presented a short introduction of two possible analogies. We examined the electron cycles and the energy levels analogies, starting from the raspberry cell case and moving to the more complex photosynthesis and semiconductor solar cell cases.

We underlined that the teacher can organize physics, chemistry and biology class activities around the raspberry solar cell. We described here the steps to build a raspberry cell, even though we recommend the do-it-yourself method only to upper secondary classes, in the presence of a teacher, with prepared glass plates and electrolyte. To demonstrate its function and discover it in action, we tested the effects of light-sources and of different dyes on the cell. Finally, we used the cell as current source to compare to an n-p junction solar cell [1],[6].

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