High-efficiency multi-junction photovoltaic cells in school physics laboratory

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Abstract

In this paper, we propose how to use high-efficiency multi-junction solar cells for didactic purposes. This activity carried out with secondary as well as high school students allows teachers to discuss sustainability issues, contributing to increase the awareness of students toward the remarkable and renewable solar energy source, and to provide students with an introductory view into modern physics aspects (quantization of energy levels), quantum mechanics (semiconductor band energies) and radiation-matter interaction. The proposed experiments aim to obtain a characteristic current-vs-voltage curve of a high-efficiency multi-junction photovoltaic cell and to verify the dependence of the light intensity on the distance from a point source of light.

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1. Introduction

The energy consumption in the world is more and more increasing due to the huge energy request coming from the emerging countries, such as China, India, etc. To face the challenge of sustainability, a solution may be the use of solar energy[1,2], since it is the most abundant renewable energy source on the Earth. The electromagnetic energy coming from the Sun can be converted into usable energy (electricity) by solar cells, whose conversion efficiency is continuously increasing due to scientific and technological progress.

The proposed activity is thought to be carried out with secondary as well as high school students to allow teachers to discuss sustainability issues, and to provide students with an introductory view into modern-physics aspects (quantization of energy levels), quantum mechanics (semi-conductor band energies) and radiation-matter interaction. Furthermore, cutting-edge research in physics can reaches school students[3,4], increasing their interest in scientific studies.

Through this activity, students can reach the following learning objectives. Students will be able to state that solar energy is the most inexhaustible source of energy, describe how the sunlight is converted directly into electric energy in photovoltaic cells and finally define the photovoltaic effect as the effect of the solar electromagnetic radiation exciting electrons in certain materials, freeing them to flow and thus produce electricity. Arguably, the latter learning objective can be reached by students of college courses.

In the paper, we propose to determine experimentally the characteristic current-vs-voltage (I-V) curve of a high-efficiency triple-junction photovoltaic cell and to verify the dependence of the light intensity on the distance from a point source of light.

2. The photovoltaic effect

The production of electric energy with solar cells takes place thanks to the microscopic properties of semiconductor materials, whose atoms can release electrons when interacting with the ultraviolet (UV), visible and infrared (IR) electromagnetic (em) radiation (photons). The process of conversion of em energy (solar radiation) into electric energy carried out by the solar cell is based on the physical phenomenon of the interaction of photons with the valence electrons in semiconductor materials, called photovoltaic (PV) effect. In the absorption process of photons with energy $h\nu$, where h is the Planck's constant and ν is the photon's frequency, the electron increases its electric potential energy of the same amount of the photon's energy and leaves its initial lower-energy state, creating a so-called *hole*. Fig. 1 shows a scheme of the electron-energy levels in a semiconductor crystal: actually, the energy levels are continuously distributed so that they can be represented by two energy bands, valence (bonded electrons) and conduction (free electrons) band, separated by an energy gap of value E_g (e.g., for Silicon, $E_g \approx 1.1$ eV). When an electron in the valence band absorbs a photon of energy $h\nu > E_g$, it undergoes a transition to an empty state in the conduction band creating a hole in the valence band. In this process, an electron-hole pair is created, which can move freely within the crystal. A review of the history of solar cells is given in Refs. [5,6] and a description of the photovoltaic effect at school level is given in Ref. [7]. A collection of resources on this subject can be found on the Photovoltaic Education Network web site[8].

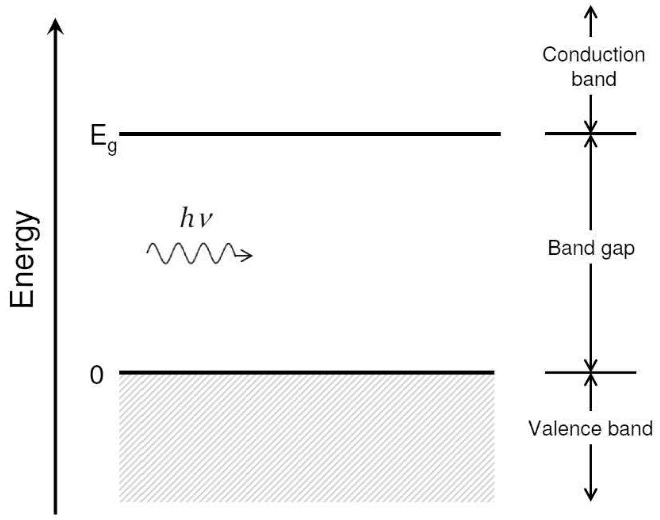

Fig. 1. Electron energy levels in a semiconductor; the valence band and the conduction band are separated by an energy gap E_g (e.g., for Silicon, $E_g \approx 1.1$ eV).

In order to use the electron-hole energy in an external circuit, it is necessary to create a p-n junction between n- and p-type semiconductors that are obtained by adding to the semiconductor specific impurity atoms (dopants). The PV cell consists of a large-area p-n junction. When incident photons create in the junction electron-hole pairs, the positive charges – holes – are pushed toward one side of the junction and the negative charges – electrons – toward the other side. If the two faces (top and bottom) of the junction are connected by a conducting wire, the free charges move through it and an electric current will be observed. When the junction is exposed to light, the electric current flows in the form of continuous current, as illustrated in fig. 2.

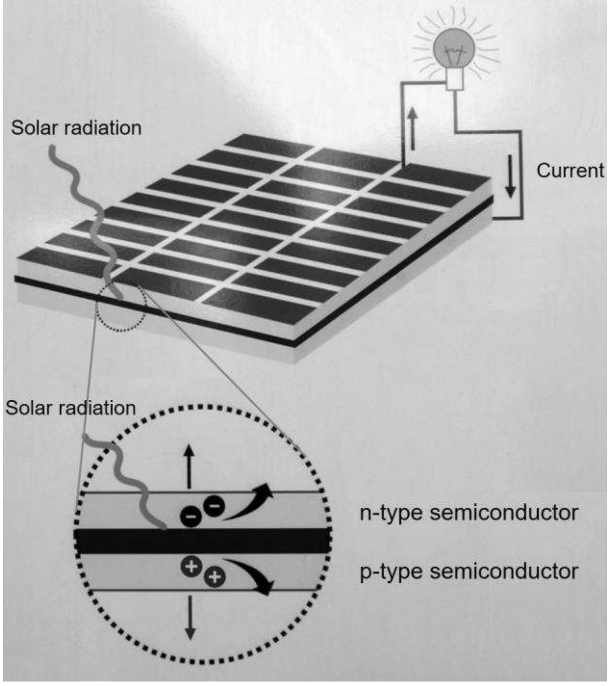

Fig. 2. Electric circuit of a PV cell under solar irradiation; under light exposition, a dc current flows through the circuit. The inset shows a detail of the p-n junction.

To describe a single-gap PV cell by an equivalent electric circuit, one can consider the current generated by the incident radiation, I_L, as represented by a constant current source, and the p-n junction of the cell as represented by a diode operating in the reverse mode. Thus, the output current, for the ideal case, is given by

$$I = I_L - I_0\,[exp(qV / kT) - 1] \tag{1}$$

where I_0 is the revers saturation current that is a measure of the thermal rate of the electron-hole pair creation process, q the electron charge, V the output voltage, k the Boltzmann constant and T the absolute temperature.

To complete the equivalent circuit, it is necessary to take into account the distributed electric resistance of the p-n junction by inserting a single lumped resistance, R_s, connected in series. Furthermore, leakage and recombination across the junction can be represented by a shunt resistance, R_{sh}. The latter usually is large enough so that its effects can be neglected[9]. The equivalent electric circuit of a single-gap PV cell is shown in fig. 3, which is obtained by an ideal current generator, a diode operating in reverse-bias mode, a shunt resistance, and a series resistance. Interestingly, the PV cell can behave like a LED diode that emits light when fed by a dc voltage of proper value.

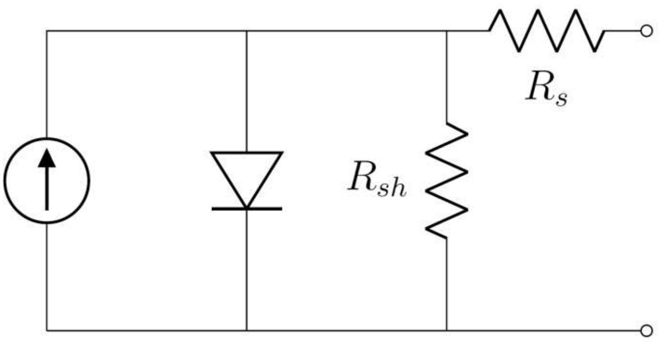

Fig. 3. Equivalent electric circuit of the single-gap PV cell: a current generator, a diode operating in reverse-bias mode, a shunt resistance R_{sh}, and a series resistance R_s[9].

Since the junction is characterized by a band gap of energy E_g, a single-junction cell can produce electric current by photons having energy larger equal than E_g, so ruling out a significant part of the solar-light spectrum and featuring large thermal losses. For this reason, single-junction cells have a low electric conversion efficiency (of the order of 10% - 20%). Conversely, solar cells having multiple p-n junctions made of different semiconductor materials, i.e. III-V compound semiconductors, InGaP with energy gap $E_g \approx 1.8$ eV, InGaS with energy gap $E_g \approx 1.4$ eV and Ge with energy gap $E_g \approx 0.7$ eV, can produce electric current in response to different wavelengths of incident light, with lower thermal losses. The performance of these cells is based on the matching between the semiconductor band gaps and the solar-light spectrum, as shown in fig. 4 where it is reported the normalized spectrum of the solar radiation $R(\lambda)$, calculated considered the Sun a black body at temperature $T_S = 5500$ K, as a function of the wavelength λ (lower x-axis) and the energy (upper x-axis) $E = h\nu = hc/\lambda$. In the plot are also indicated (vertical dashed lines) the values of the energy gaps of the triple p-n junctions made of InGaP ($E_g \approx 1.8$ eV), InGaS ($E_g \approx 1.4$ eV) and Ge ($E_g \approx 0.7$ eV). A multi-junction solar cell will therefore produce electric current using a wider part of the solar-light spectrum, increasing considerably the conversion efficiency (up to 50%).

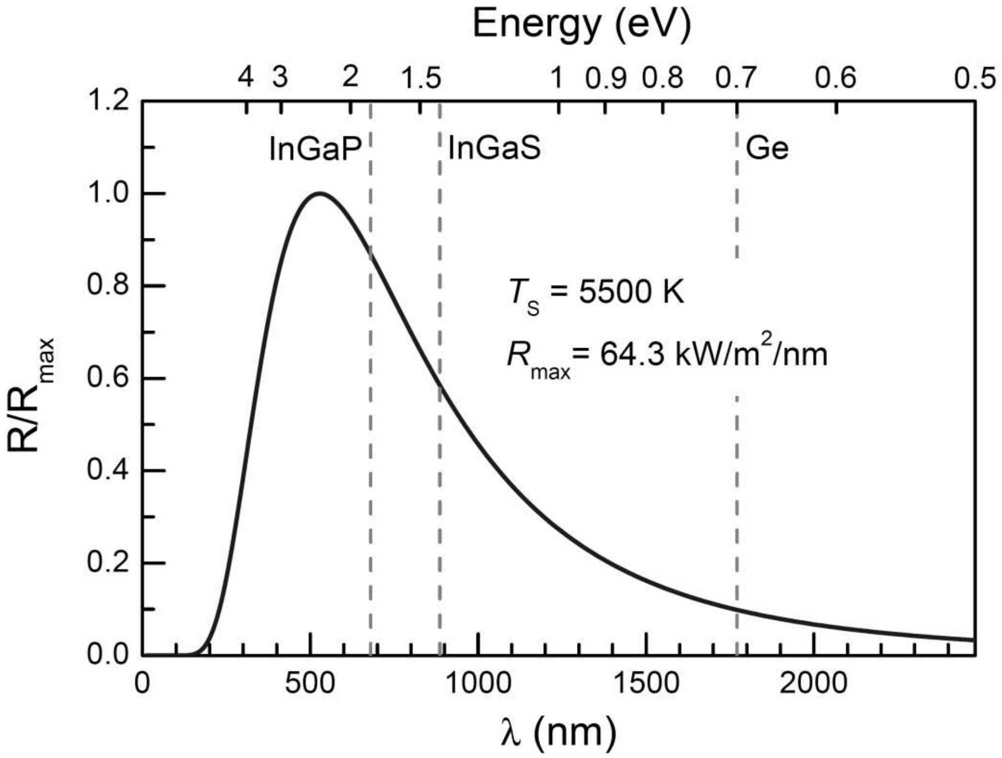

Fig. 4. Normalized spectrum of the radiation emitted by the Sun at the temperature $T_S = 5500$ K. The plot shows the normalized power per unit of surface emitted by the black body in the wavelength range [λ, $\lambda + d\lambda$] as a function of the wavelength λ (lower x-axis) and the energy (upper x-axis). Vertical dashed lines indicate the values of the energy gaps of InGaP ($E_g \approx 1.8$ eV), InGaS ($E_g \approx 1.4$ eV) and Ge ($E_g \approx 0.7$ eV).

The equivalent electric circuit of multi-junction solar cells is obtained connecting in series a number of single-junction-cell circuits equal to the number of the gaps in the multi-junction cell. From the technological point of view, as the multi-junction cells based on the III-V compound semiconductors have small dimensions (the irradiated area is typically 10×10 mm^2), their utilization in photovoltaic plants has stimulated a rapid growth of studies of solar cells under higher solar concentration by using optical devices to capture light[10-13].

3. Experimental apparatus and results

The high efficiency of multi-junction-semiconductor solar cells allows one to use, for didactic purposes, a single cell (of approximate dimension 10×10 mm^2) illuminated by an incandescent lamp as a light source instead of solar radiation. This system can be conveniently used in school physics laboratories during the indoor activities at any time, even in a cloudy winter day[14,15]. Fig. 5 shows the commercial InGaP/InGaS/Ge triple-junction PV cell, provided by Taicrystal International Technologies Corporation[16] at an affordable cost (about ten Euro each), which we used in the experiments.

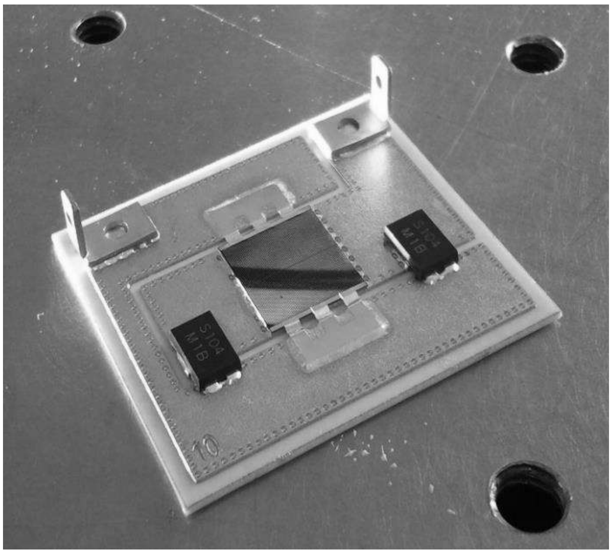

Fig. 5. The commercial InGaP/InGaS/Ge triple-junction PV cell provided by Taicrystal International Technologies Corporation[16], which we used in the experiment.

In order to study the I-V (current vs voltage) characteristic of the PV cell, we connect the cell to a variable load resistance R_L (varying from 0 to 5 kΩ), a high-impedance voltmeter and a low-impedance ammeter[15], as shown schematically in fig. 6. These measurements can also be easily performed by using the PASCO Voltage-Current Sensor PS-2115 with the interface and the software for data collection and analysis[17].

After locating the PV cell on a horizontal plane and mounting an incandescent lamp on a vertical shaft, such as to illuminate uniformly the PV cell (see the experimental setup in fig. 7), one measures the I-V characteristic of the PV cell, on varying the load resistance from 0 to its maximum value. A typical I-V characteristic of the cell is shown in fig. 8. The I-V curve allows one to determine the short-circuit current I_{sc}, detected for $R_L = 0$ and the open-circuit voltage V_{oc}, detected for $R_L \to \infty$. To obtain the electric power generated by the PV cell, we plot the product of V and I as a function of V, from which we determine the max electrical peak power, P_{mpp}, with an uncertainty of about 0.2 mW. The maximum power obtained in this configuration is about 13 mW.

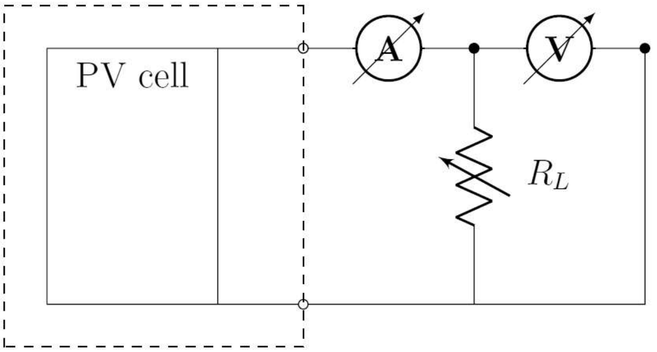

Fig. 6. Schematic electric circuit diagram for determining the I-V characteristic of the multi-junction PV cell. Here, **A** denotes the ammeter, **V** the voltmeter and R_L the variable load resistance.

From the I-V characteristic of the PV cell detected at different distances of the lamp from the PV cell, we determine P_{mpp} as a function of the light-source distance. The obtained experimental results are reported in fig. 9. The lamp height from the cell is measured by a vertical ruler (see fig. 7). In particular, we measure the distance from the cell and a fixed point on the lamp, with an uncertainty of about 2 mm. As one can see from the plot, on increasing the distance of the lamp from the cell, the generated electric power reduces.

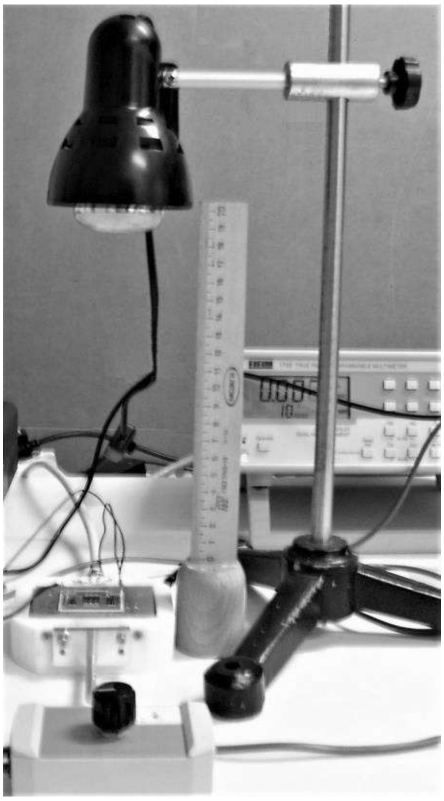

Fig. 7. Experimental apparatus.

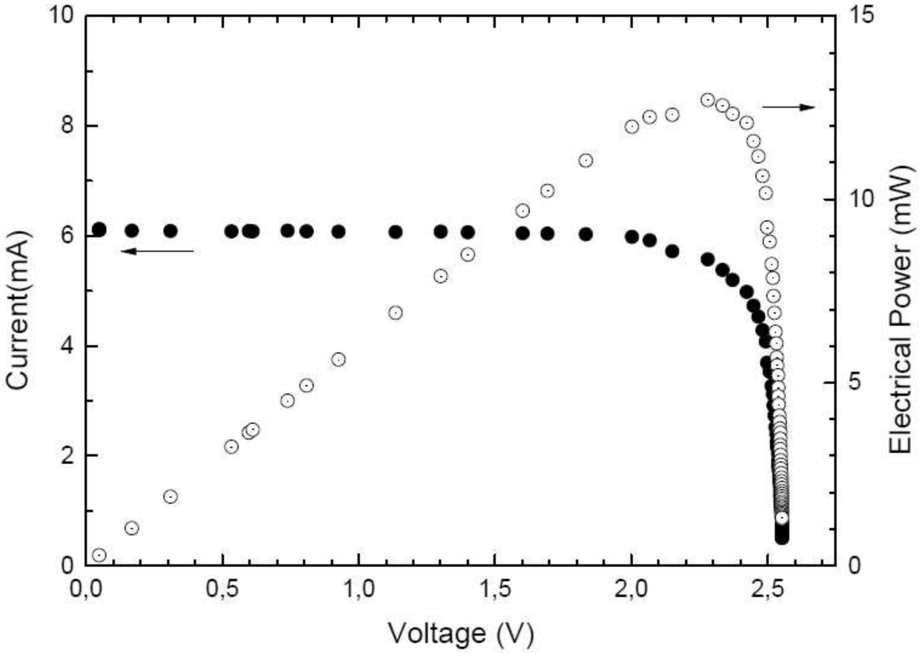

Fig. 8. I-V characteristic of the cell. On the right axis is reported the electric power obtained multiplying voltage times current. From the plot, the short-circuit current I_{sc}, detected for $R_L = 0$, is $I_{sc} \approx 6.2$ mA and the open-circuit voltage V_{oc}, detected for $R_L \to \infty$, is $V_{oc} \approx 2.55$ V.

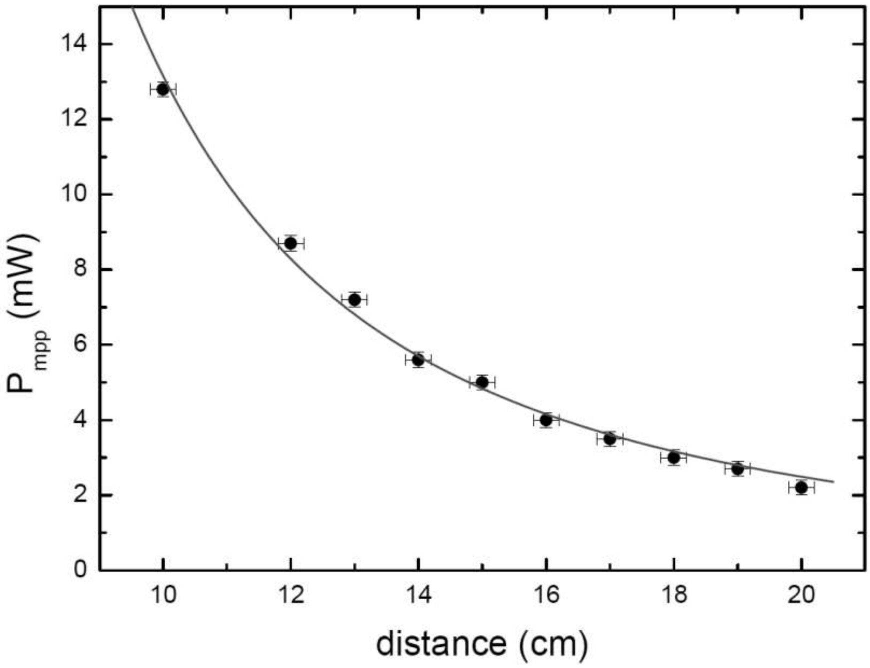

Fig. 9. Electric power as a function of the distance between the lamp and the cell. The lamp height from the cell is measured by a vertical ruler, as shown in fig. 7. Symbols are experimental data; the line is the best-fit curve obtained as described in the text.

4. Discussion

The behaviour of the I-V curve can be understood looking at the equivalent electric circuits of figs. 3 and 6. At low currents, related to large values of R_L, the potential drop at R_s is small and then V_{out} is large. Conversely, at the high currents obtained for small values of R_L, the potential drop at R_s is large and then V_{out} is small. It is worth noting that the short-circuit current $I_{sc} \approx 6.2$ mA, detected for $R_L = 0$, corresponds to I_L of eq. (1); it is the largest current which may be drawn from the solar cell due to the generation and collection of light-generated carriers. The open-circuit voltage $V_{oc} \approx 2.55$ V, detected for $R_L \to \infty$, is the maximum voltage available from the solar cell and it corresponds to the bias of the solar-cell junctions with the light-generated current. By comparing the single-junction and the triple-junction cell, it results that this latter can extract a larger electric power, given by the product of the current and the voltage, since the voltage of the triple-junction cell is larger because of the series of three junctions. Obviously, from the I-V curve one can determine the max peak power at intermediate current and voltage values.

The em power $\mathcal{P}$ (energy per unit of time) passing through a unit of surface area orthogonal to the direction of the wave propagation is the light intensity $\mathcal{I}$. Let us consider a point source of power $\mathcal{P}$, which emits light isotropically, and a spherical surface of area $S = 4\pi r^2$ centered on the source. If the whole energy arrives on the spherical surface, the light intensity will depend on the distance, r, from the light source as

$$\mathcal{I} = \mathcal{P}/4\pi r^2 \qquad (2)$$

The results shown in fig. 9 can be explained by considering that the intensity of light that reaches the surface of the cell depends roughly on r^{-2}. So, considering that, as the light intensity varies the cell voltage does not appreciably change and only the current decreases, the electric power P will be proportional to the light intensity $\mathcal{I}$, obtaining the following relation

$$P \propto \mathcal{I} \propto r^{-2} \qquad (3)$$

Since the incandescent lamp is not a point source and furthermore the lamp bell tends to concentrate the light, it is difficult to determine the point at which one can consider the lamp be located as the equivalent point source of light. Practically, it means that we can measure the real distance between the cell and the light source except for a fixed length r_0. In order to find r_0, we have measured the distance from a fixed point on the lamp and then we have found the unknown r_0 value by fitting the experimental data reported in fig. 9 with the function

$$P(r) = A/(r - r_0)^2 \tag{4}$$

From the best fit of experimental data, we obtain $A = (780 \pm 60)$ mW cm^2 and $r_0 = (2.3 \pm 0.3)$ cm.

The electric power generated by the PV cell is proportional to the light intensity. Since the light intensity depends on the inverse square of the distance of the PV cell from the light source, also the power generated depends on the inverse square of such a distance. In this experiment, errors are certainly due to the effect of the background light coming from the surrounding environment. These sources of error affect the data in such a way as to not obtain a perfect fit of the theoretical curve to the experimental data. Furthermore, an important point to be stressed is that the spectrum of the light emitted by the Sun and all the incandescent lamps can be described by the law of black-body emission at different temperatures. For this reason, an incandescent lamp is a good substitute of solar radiation, when the direct sunlight is not available[18].

5. Conclusion

We remark that, even if the didactic experiment regards the PV effect in general, it is easily performed by the setup above described thanks to the non-standard multi-junction PV cell. In fact, its small dimensions allow one to uniformly irradiate its active area, at any distance from the light source, and its high conversion efficiency returns easily detectable values of current and voltage. Both these characteristics make advantageous the use of multi-junction PV cells with respect to standard Si cells. The experiment is certainly instructive for both the conversion of solar energy into electrical energy and the method to fit the experimental data.

To meet the class requirements, the proposed laboratory activity can be easily adapted to various level of experimental and theoretical sophistication. After completing these activities, students will be able to state that solar energy is the most inexhaustible source of energy, describe how the sunlight is converted directly into electric energy in photovoltaic cells and finally, for high school students, define the photovoltaic effect.

In conclusion, we have shown that cutting-edge research in physics can helpfully reach secondary as well as high school students, exploiting the potentialities of laboratory activities as a key to success in stimulating students to learn and to be interested in scientific topics. Furthermore, this activity allows teachers to discuss topics about renewable energy and sustainability issues, contributing to increase the awareness of students toward this remarkable energy source, and to discuss, at an elementary level, quantization of energy levels and band energies in semiconductor.

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