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Characterization of photovoltaic modules for low-power indoor application

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HIGHLIGHTS

- ▶ Characterization of commercially available third generation photovoltaic modules.
- ▶ Characterization performed under artificial light conditions only.
- ▶ Characterization performed under mixed natural/artificial illumination conditions.
- ▶ Some modules present a decrease in their performances under fluorescent tubes.
- ▶ Si–μsph and DSC modules are usable for low-power devices in real indoor conditions.

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ABSTRACT

Photovoltaic energy generation is envisaged as an efficient, natural and valuable energy source not only for outdoor but also for indoor applications, even if it is often difficult to give an adequate description of the indoor illumination conditions, and till now no (international) norms regulate the characterization of solar cells under the particular indoor conditions.

In this work commercially available photovoltaic modules have been measured under artificial light conditions using an appositely designed experimental set-up, and under mixed natural/artificial illumination in real indoor conditions. These modules are based on completely different physical and chemical concepts, from semiconducting amorphous *p–i–n* junctions to photoelectrochemical cells based on TiO_2 nano-particles, to semiconducting polymers, to crystalline silicon micro-spheres. Aim of this work is to compare their performances in view of possible indoor applications for low-power devices.

1. Introduction

Low consumption electronic devices such as wireless phones, personal organizers, tablet computers, remote controllers and sensors, are undergoing a continuous growth. All these devices need power, and generally the power needs are increasing together with the functionality of the device and decreasing with the progress and the improvements in the integrated circuits and in the batteries technologies. Moreover, all these devices usually work under indoor conditions, given by a mixture of natural and artificial light. Even if it is often difficult and quite impossible to give an adequate description of the indoor illumination conditions, photovoltaic energy generation is envisaged as an efficient, natural and valuable energy source not only for outdoor but also for indoor applications.

The photovoltaics market for terrestrial applications is nowadays dominated by crystalline silicon (both in mono and poly-crystalline form), which generally gives the best compromise between costs and performances: in July 2011 in Europe, the modules reached costs of around 1.2 €/Wp and efficiencies as high as 20% under direct solar illumination [1]. However it is well known that, under non-direct radiation, amorphous thin films, nanostructured materials and also polymers [2] can give better absorption of the light with respect to crystalline solids. For this reason the so called "second and third generation" solar cells should be more appealing for usage under both direct and diffuse radiation conditions: the "second generation" solar cells are made by thin films of amorphous silicon, cadmium telluride, copper indium gallium selenide, etc.; while the dye sensitized solar cells (fabricated using a nanostructured TiO_2 film) [3], the organic solar cells (made with polymers) [4] and also the recently proposed solar cells obtained using silicon micro-spheres [5] are often identified as the "third generation" or "emerging concepts" in photovoltaics [6].

Recently, great attention has been devoted to test PV solar modules under year-round typical weather conditions [7], to simulate different operating conditions such as solar intensities [8] and partial shadowing [9]. Nevertheless, the characterization of market

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available photovoltaic cells and modules is generally performed under Standard Testing Conditions: 1000 W/m^2 (1 sun), direct normal irradiance intensity with Air Mass 1.5 (AM1.5) spectral composition and temperature of 25 °C. In practice, no solar cell experiences such conditions; however they are useful for establishing valuable comparisons. It must be taken into account that these conditions do not represent indoor environments, where illumination intensities are always lower, typically in the range 0.05–5 mW/cm^2, depending on the light sources and lightening conditions, and the spectral composition diverges from AM1.5, due to the presence of reflected or diffused light and due to the presence of artificial light sources, window glazing and filtering effects.

Till now no (international) norms regulate the characterization of solar cells under the particular indoor conditions, and furthermore, the indoor light intensity levels are usually given in terms of photometric rather than radiometric units, which renders difficult the comparisons.

Some papers have been published on the modeling of lightening conditions available in indoor situations such as offices, or domestic ambient, through the study of the variations in intensity and color of the daylight [10], or using Computer Aided Design software for ray-tracing in 3-dimensional sceneries [11], or simulating and measuring the user presence in different months of the year [12]. For outdoor conditions the solar spectrum is varying with the weather, with the day-time and with the year period; for indoor conditions such effects can be less important, however all the results are strongly dependent on the artificial light sources which are used. Other works have been made for simulating the solar cells performances under low irradiance conditions [13–16]: aim of these works was to obtain models for calculating important parameters such as the short circuit current and the efficiencies of different kinds of solar cells exposed to different indoor conditions, in particular to different artificial lamps. Also, some papers have suggested and evaluated the utilization of photovoltaics for low-power indoor devices such as remote sensors [17], wireless computer mouses [18], organic light emitting diodes [19], smart clothing [20] and also emergency street lights [21].

In this work commercially available photovoltaic modules have been measured under artificial light conditions using an appositely designed experimental set-up, and under mixed natural/artificial illumination in real indoor conditions. These modules are based on different physical and chemical concepts, from semiconducting amorphous *p–i–n* junctions to photoelectrochemical cells based on TiO_2 nano-particles, to semiconducting polymers, to crystalline silicon micro-spheres. Aim of this work is to compare their performances in view of possible indoor applications for low-power devices.

The paper is organized as follows. Section 2 is devoted to experimental, explaining the used units, light sources and PV modules, together with the measurements apparatuses. In Section 3 the theory about radiometric and photometric units and the correlation between the short circuit current density and the quantum efficiency of a solar cell are explained. In Section 4 the performances of the different PV modules obtained under artificial light illumination are presented and discussed and the results of the two best-performing PV modules under artificial and natural daylight illumination are reported. Section 5 is devoted to the conclusions.

2. Material and methods

2.1. Artificial light sources

For the present work different lamps have been used: one incandescent lamp (model 005002-ST1340 from Orbitec), one halogen lamp (model FMW-FG 15057 from Eiko) and one low-consuming fluorescent lamp (model 2050 from Duralux). Their spectral irradiances have been measured by means of a StellarNet EPP2000-UVN spectrometer and a Molectron EPM1000 wattmeter. The illuminance has been measured by a luxmeter (model HD2102.2 from DeltaOhm).

2.2. Available solar modules for indoor applications

Different commercially available solar modules have been acquired and characterized for this work. The first type (referred in this work as "Si–μsph") is based on spherical and crystalline micro-cells, obtained from melt silicon, with micro-reflector cups on a bendable aluminum substrate capable of significantly reducing conventional production costs, fabricated by the Japanese company Clean Venture 21 (Jap. Patent 3490969). The examined modules are the models CVFM-O030T1-BK, with active area of 330 cm^2 and four interconnected unit cells, and CVFM-O045T1-BK, with an area of 480 cm^2 and six interconnected unit cells. The second one (referred as "CIGS") is a thin-film based solar module in copper indium gallium selenide from Ascent Solar (Ascent Solar's WaveSol™), model SWSME-0040-024-DB-05, with an area of 450 cm^2. These flexible modules are manufactured on ultra-thin plastic substrates and are particularly suggested for portable energy generation with non-flat surfaces and light-weight devices. Regarding the third type (referred as "organic"), two solar modules manufactured by Konarka (models A10-20-31-00 and 220-40-31-00, with areas of 120 cm^2 and 1260 cm^2 respectively) have been chosen. These modules are based on patented photo-reactive materials made from conductive polymers such as P3HT, poly(3-hexylthiophene), and organic fullerene-based nano-engineered materials invented by the Nobel Prize winner, Dr. Alan Heeger; the material is coated onto flexible substrates using roll-to-roll manufacturing, and the final product (Konarka Power Plastic®) is optimized for working both indoors and outdoors. The last one (referred as "DSC") is fabricated using dye sensitized solar cells, which, since the first paper of 1991 [3], are considered among the most promising candidates for the next-generation solar devices with low production costs, simple fabrication process and good efficiency in energy conversion. The examined module (serio 3030w31 from Solaronix) is a serially interconnected dye solar cell module, which consists of 31 cells integrated on a same glass substrate, with an area of 720 cm^2, obtained by means of a screen printed TiO_2 nanostructured layer, a metal–organic dye (Ruthenizer 535-bis TBA), a liquid iodine-based electrolyte and a platinum counter-electrode.

2.3. Experimental set-up for the characterization

The photovoltaic characterization of the modules was carried out using a dedicated set-up able to simulate an indoor ambient. It consisted of a wooden box whose interior was covered by a white-colored water paint for inside use, anti-transpiring and anti-static, commercially available (Sikkens Alpha Isolux SF), in order to simulate the artificial lightening conditions of an interior local with radiation-diffusing walls. The chamber dimensions are 70 × 40 × 40 cm^3, the light sources are located on the upper wall. The PV modules can be positioned on the lateral wall or on the bottom wall: this permits to verify if any difference of the photovoltaic performances can be related to the position; the distance between the lamp and the PV module is of about 40 cm in both the cases. The illuminance level was tuned by adjusting the voltage applied to the lamps using an external power supply (model SPD-3606 from GWInstek).

Other measurements have been performed in mixed artificial/natural daylight illumination. The modules were put in vertical position on the wall of the laboratory room, that is equipped with a window and illuminated by a Neon tube (Philips Master TL5 HO 54 W/840). At interval of 30 min from morning to afternoon, 20 measurements of the illuminance level and of the *I–V* performance were undertaken.

For all the experiments, the *I–V* curves have been collected using a Keithley 2440 source measure unit.

3. Theory

3.1. Radiometric and photometric units

When evaluating the light generated by different sources, from the natural sunlight to the artificial lamps, two different units are generally used: one radiometric and one photometric. Radiometric units refer to the power (in watt) of the total spectrum, while photometric units make use of the lux, and refer to the sensitivity of the human eye, described by the CIE international standard curve $V(\lambda)$ which practically limits the response only to the visible region (360–760 nm). The "irradiance" E (measured in W/m^2) is the radiometric unit, and it is related to the photometric "illuminance" E_{phot} (measured in lux; 1 lux = 1 lm/m^2) through the relationship [14]:

$$E = \int_0^\infty E(\lambda)d\lambda = K_m \int_0^\infty E_{phot}(\lambda)V(\lambda)d\lambda \tag{1}$$

where $E(\lambda)$ is the "spectral irradiance" (in Wm^{-2} nm^{-1}) and K_m, called maximum spectral efficacy (K_m = 683 lm/W), is part of the empirical definition of the lumen. The luminous efficiency, in lm/W, is thus 683 if all the radiation is at 555 nm, and is always less for a source with a distributed spectrum.

3.2. Short circuit current density and quantum efficiency

The short circuit current density of a solar cell, J_{sc}, can be obtained calculating the integral over all the wavelengths of the photon flux Φ multiplied by the solar cell quantum efficiency IPCE and by the electron charge q, by means of the well-known formula [14]:

$$J_{sc} = \int_0^\infty q \cdot \Phi(\lambda) \cdot \mathrm{IPCE}(\lambda)d\lambda \tag{2}$$

The photon flux incident on the cell can be evaluated as:

$$\Phi(\lambda) = \frac{E(\lambda)}{hc/\lambda} \tag{3}$$

where $E(\lambda)$ is the spectral irradiance (in W per unit square per unit wavelength), h is the Planck constant and c is the speed of the light. The product under the integral in the J_{sc} formula (2) can be considered as a "spectral short circuit current density".

4. Results and discussion

4.1. Artificial light illumination

4.1.1. Spectra of artificial light sources and of solar cells quantum efficiencies

In Fig. 1 the measured spectral irradiances of the different lamps are reported. In order to compare the same lighting conditions, the irradiance values have been obtained to an illumination of 1000 lux, measuring the irradiance of each lamp with a thermopile-based wattmeter, and normalized assuming equal to 1 the irradiance of the fluorescent lamp at 612 nm. The examined sources exhibit very different spectral behaviors and are also covering different wavelength regions. The fluorescent lamps have been appositely designed for maximizing the emission in the visible region, and obtaining very high luminous efficiency, while both halogen and incandescent lamps are covering the largest portion of the spectrum, arriving to emit also in the near infrared region (760–1100 nm) which can be useful for solar cells, but is not contributing to the human eye visibility. In Fig. 2 the incident photon-to-electron conversion efficiency (IPCE) spectra for the different solar cells used to fabricate the modules which have been characterized in this work are reported. All these spectra have been given by the constructors, and it is important to notice that they have been measured on single, small-area cells, under simulated AM1.5 illumination.

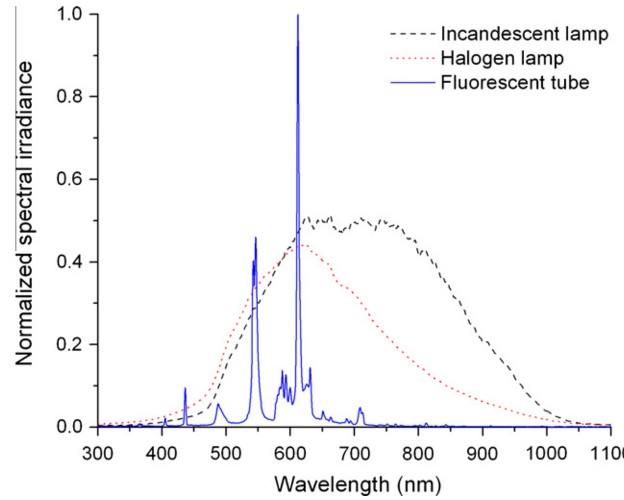

Fig. 1. Normalized spectral irradiance for the different artificial light sources measured at 1000 lux.

4.1.2. Indoor I–V characterizations of the solar modules under different artificial light sources

In Table 1 the parameters obtained from *I–V* characterization of the solar modules under the different artificial light sources are reported. All the values are related to the measurement taken with the modules put in the bottom of the box, but no significant difference was observed when modules were measured at the wall. When using fluorescent lamps, due to their very low electrical consumption, it is possible to obtain very high illuminance values: for this reason we reported the values obtained from 1000 to 3000 lux with incandescent and halogen lamp, while under fluorescent

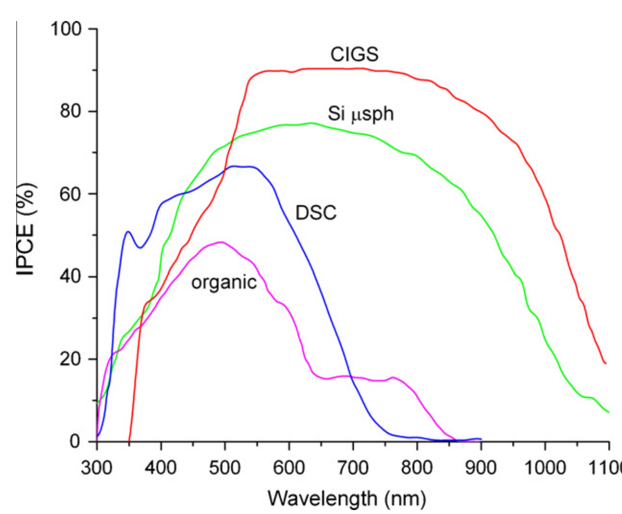

Fig. 2. Incident photon–to–electron conversion efficiencies for the solar cells used in the characterized modules.

Table 1
Measured short circuit current densities, open circuit voltages, fill factors and photovoltaic conversion efficiencies of PV modules under different illumination conditions.

Source	Lux	Si–μsph 480 cm^3				CIGS 450 cm^2				Organic 1260 cm^2				DSC 720 cm^2			
		J_{sc} (μA/cm^2)	V_{sc} (V)	FF (%)	PCE (%)	J_{sc} (μA/cm^2)	V_{sc} (V)	FF (%)	PCE (%)	J_{sc} (μA/cm^2)	V_{sc} (V)	FF (%)	PCE (%)	J_{sc} (μA/cm^2)	V_{sc} (V)	FF (%)	PCE (%)
Incandescent lamp	1000	99.8	2.4	75	3.63	27.0	14.0	35	2.71	3.7	7.2	51	0.27	1.9	13.2	42	0.21
	2000	170.0	2.6	76	4.68	44.3	16.5	41	4.15	6.9	8.0	51	0.39	3.9	14 5	50	0.40
	3000	221.7	2.8	75	5.32	58.7	17.9	44	5.29	9.9	8.4	50	0.48	5.7	14.9	54	0.53
Halogen lamp	1000	77.8	2.3	65	3.58	18.2	8.9	29	1.46	3.1	7.0	50	0.34	1.6	13.1	39	0.25
	2000	130.3	2.5	66	4.60	28.9	11.7	33	1.54	5.4	7.6	51	0.45	3.3	14.5	48	0.50
	3000	180.7	2.6	68	5.47	39.0	13.3	35	2.09	7.9	8.0	52	0.58	4.8	15.1	52	0.67
Fluorescent tube	1000	9.59	1.6	61	1.89	1.8	2.0	23	0.17	1.2	6.0	48	0.68	1.2	11.7	26	0.75
	2000	17.0	1.8	66	3.37	3.5	3.5	24	0.49	1.9	6.6	49	1.02	2.5	13.7	37	2.08
	3000	23.8	2.0	65	4.17	5.7	5.5	25	1.06	3.0	7.2	52	1.52	3.6	14.4	42	3.01
	4000	34.9	2.1	65	5.70	7.2	6.5	26	1.38	4.3	7.6	51	1.88	4.9	14.8	45	3.70
	5000	39.9	2.2	69	5.89	8.6	7.5	27	1.69	5.0	7.8	54	2.06	6.2	15.2	48	4.41

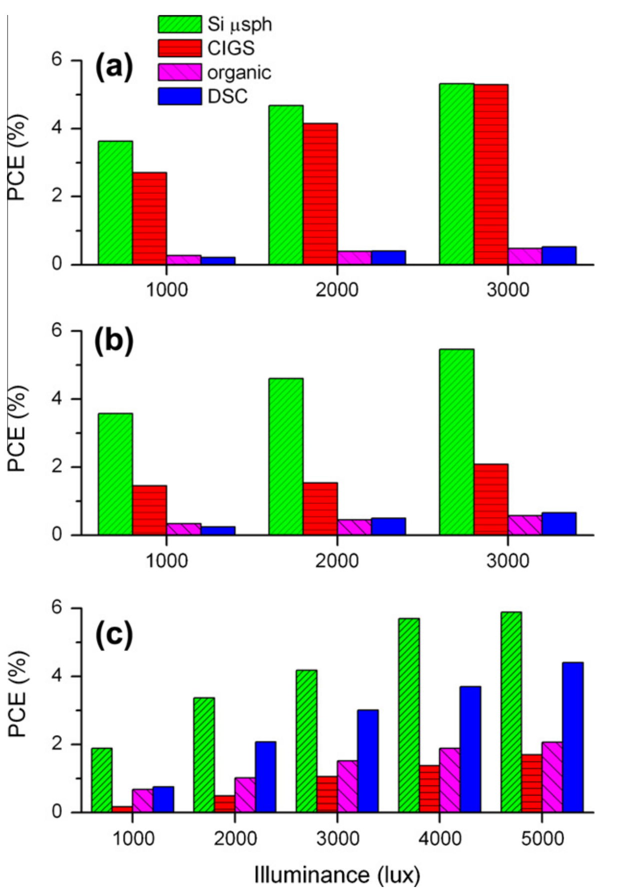

Fig. 3. Photovoltaic conversion efficiencies of PV modules under different illuminance conditions for different artificial light sources: (a) incandescent lamp, (b) halogen lamp and (c) fluorescent tube.

lamp also the values measured at 4000 and 5000 lux have been reported. Only the results obtained on larger area modules have been shown, and it has to be noticed that the large differences in the open circuit voltage values are not only due to the different types of solar cells but also to the different number of interconnected cells in the modules. In Fig. 3 the photovoltaic conversion efficiencies (PCE) of the same modules of Table 1 and in Fig. 4 the maximum power obtainable for the DSC and Si–μsph modules are reported. From the comparison of the data some interesting

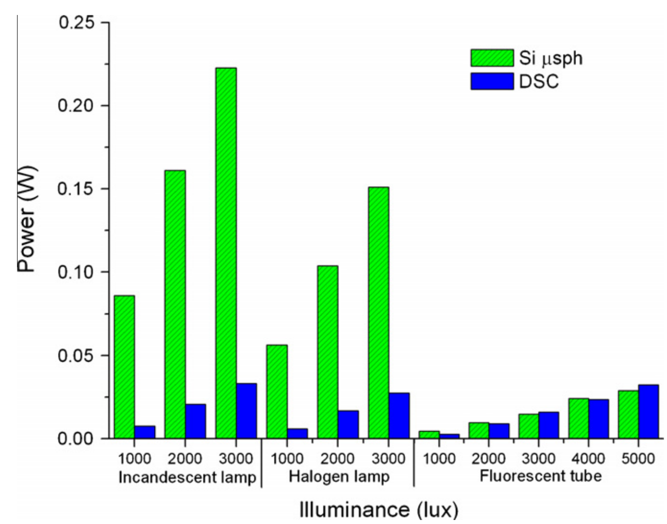

Fig. 4. Maximum power obtained from *I*–*V* characterization for Si–μsph and DSC modules under different illuminance conditions for different artificial light sources.

features can be observed. Under the incandescent lamp, the Si–μsph and the CIGS modules clearly exhibit better performances with PCE higher than 2.7%, while the DSC and organic modules conversion efficiencies remain lower than 0.7%. The CIGS module efficiencies decrease under the halogen and mostly under the fluorescent lamps, while the DSC and organic modules PCE values strongly increase with fluorescent tubes. In particular under the fluorescent tube the DSC efficiencies increase from 0.75% to 4.41% with increasing illuminance from 1000 lux to 5000 lux, while for the organic module the increase is from 0.68% to 2.06%. It has also to be observed that, for the organic modules, the small area sample (120 cm^2, here not reported) exhibited higher PCE: quite two times higher under incandescent and halogen lamp and three times under fluorescent tube. Furthermore, from Fig. 4 it appears that the DSC module of 720 cm^2 can arrive to give 30–35 mW with both incandescent (at 3000 lux) and fluorescent (at 5000 lux) lamps, while with the halogen lamp the maximum obtainable power is somewhat less than 25 mW. With the silicon-microspheres module the obtainable maximum powers are greatly higher: till to 220 mW under incandescent and till to 150 mW under halogen lamps.

On the other side, under fluorescent lamps which are nowadays the most used artificial light sources, the Si–μsph performance is of the same order of the DSC module. The DSC module has a larger

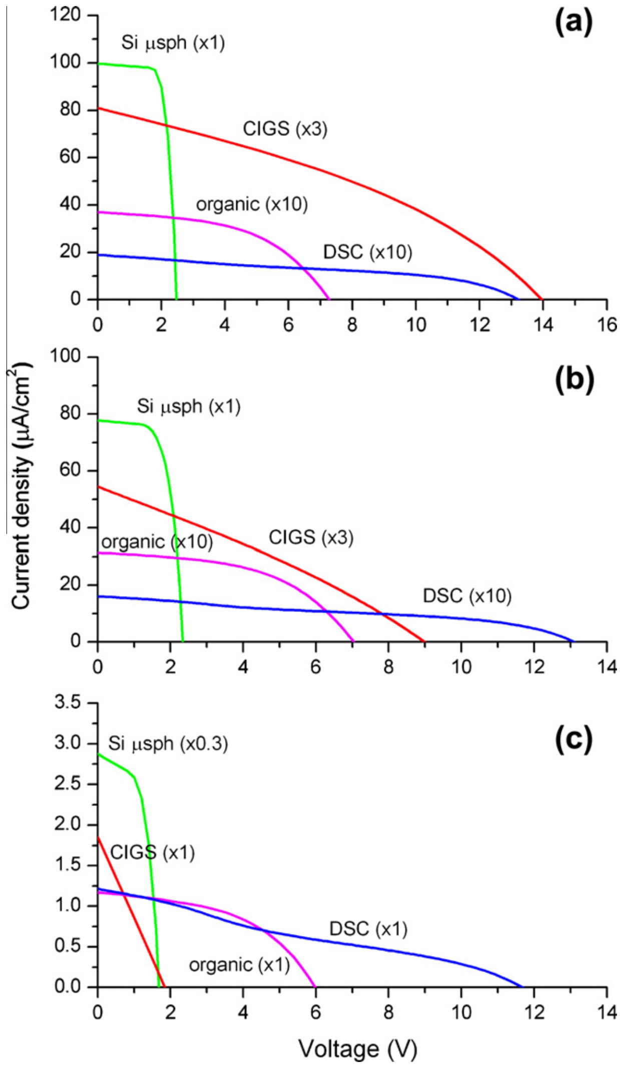

Fig. 5. *J–V* curves under 1000 lux illuminance for different artificial light sources: (a) incandescent lamp, (b) halogen lamp and (c) fluorescent tube. The curves were multiplied by different constant values (reported on the graphs) for scaling purposes.

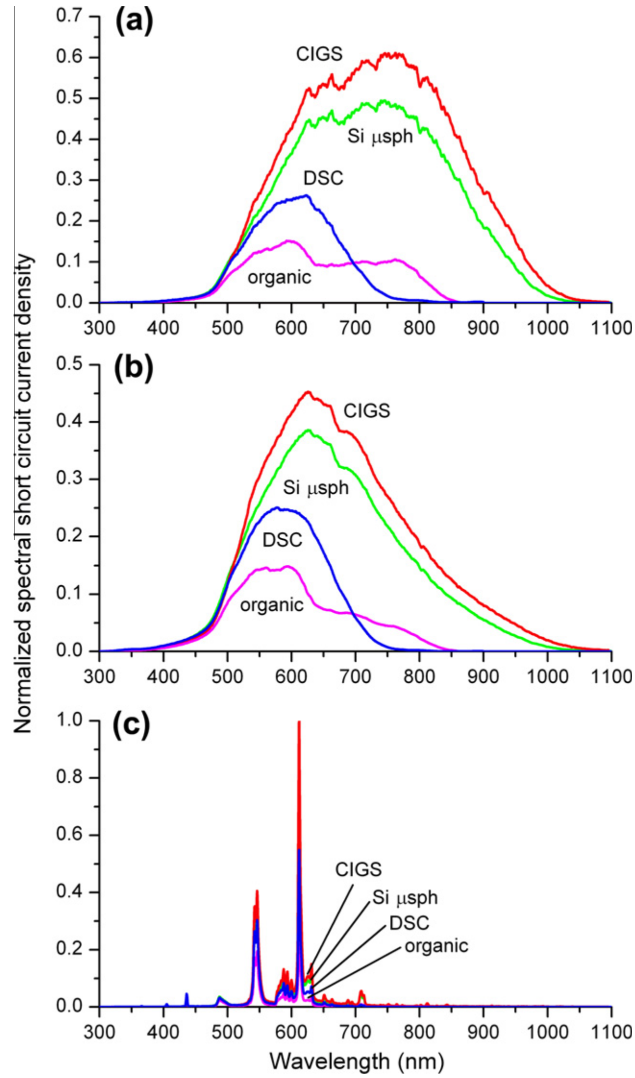

Fig. 6. Calculated spectral short circuit current density for the different artificial light sources at 1000 lux: (a) incandescent lamp, (b) halogen lamp and (c) fluorescent tube. The spectra were normalized assuming the maximum value for the CIGS cell under fluorescent tube equal to 1.

area (720 cm^2 with respect to 480 cm^2 for Si–μsph), but presents some advantages like the partial transparency, and the possibility of different screen-printed shapes of the photoelectrodes. All these results were to be expected from the comparison between the spectral emittance of the light sources (Fig. 1) and the solar cells quantum efficiencies (Fig. 2): the incandescent and halogen lamps completely cover the spectral response region of Si and CIGS solar cells, while a large portion of their spectrum cannot be useful for electrical energy generation in organic and dye sensitized cells. In order to better understand the behavior of the examined solar modules, in Fig. 5 their *J–V* curves are reported for the different lamps at 1000 lux illuminance. It is clearly visible the reduction both in the open circuit voltage V_{OC} and in the fill factor *FF* for CIGS module under the halogen and fluorescent lamp, which has already been reported and attributed to the parallel resistance parameter, R_{shunt} [22]. On the contrary, the DSC and organic modules *FF* is maintained at higher values also in low illuminance conditions, but their obtainable powers remain for all the examined indoor illuminations lower than 35 mW.

4.1.3. Comparison between experimental and calculated J_{sc}

Using the measured spectral irradiance $E(\lambda)$ (reported in Fig. 1 for 1000 lux) and the solar cell quantum efficiencies IPCE(λ) (reported in Fig. 2) for the four types of solar cells under the different illuminations, the term under the integral in Eq. (2), that is the product

$$q \cdot \Phi(\lambda) \cdot \mathrm{IPCE}(\lambda) = q/hc \cdot \lambda \cdot E(\lambda) \cdot \mathrm{IPCE}(\lambda) \quad (4)$$

has been evaluated and the normalized results are reported in Fig. 6 for the illuminance value of 1000 lux (similar plots have been obtained for 2000 and 3000 lux). The total area under the curves is proportional to the calculated short circuit current density, which should be obtainable from one solar cell, with quantum efficiency IPCE(λ), under the given illumination conditions.

Observing in detail the figures the four cells evidence a completely different behavior under the incandescent and the halogen lamps, while not strong differences are observable for the curves obtained with the fluorescent tube. In fact the fluorescent tube emission spectrum, with its very narrow and high peaks, for all the cells "dominates" the trend of the curve, limiting it in the visible region (400–700 nm); with fluorescent tube (Fig. 6c) the IPCE(λ) acts essentially as a "scaling factor", so – even with a very similar trend – the obtainable spectral J_{sc} is higher for the CIGS cell because its quantum efficiency is higher in the visible region. On

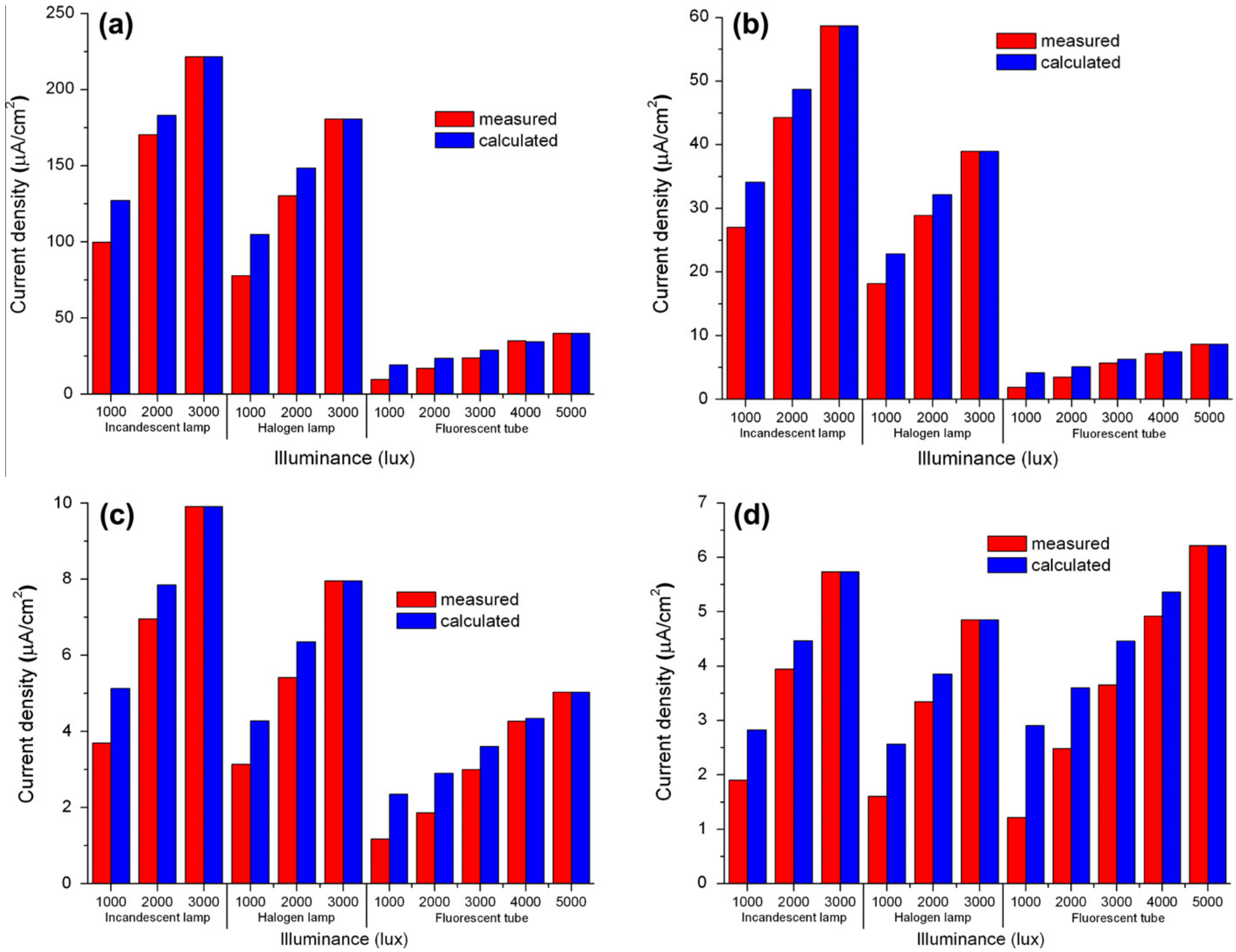

Fig. 7. Comparison of measured and calculated J_{sc} values under different light conditions for different PV modules: (a) Si–μsph, (b) CIGS, (c) organic and (d) DSC.

the contrary, under the halogen and incandescent lamp the CIGS and Si–μsph curves cover all the wavelengths from 300 to 1100 nm, and for these cells the total areas under the curve (J_{sc}) are higher; the organic and DSC curves clearly show the respective IPCE(λ) trends, arriving till to 850 nm for organic cell and only to 750 nm for DSC, but with lower values of the total area in the case of organic. Fig. 6 clearly shows that the CIGS cells give the highest values of the spectral current density under all the used light sources: this fact is due to the very high values of IPCE(λ) given by the constructor (Fig. 2). It has nevertheless to be noted that CIGS modules do not exhibit the best electrical behavior: in particular both the PCE (Fig. 3) and the short circuit current density (Fig. 5) drastically reduce under halogen and fluorescent lamp illumination.

Finally, it is not possible to compare the theoretical values of J_{sc} for a single cell, obtained from the integral of the spectral current density, with the short circuit currents experimentally obtained from the I–V measurements on the modules. The calculated values are obviously higher, due to the fact that the modules are composed by a large number of cells and that no losses (due to the electrical resistances, to the module packaging and to any other effect related to the cell/module assembly) have been taken into account. We compared nevertheless the trends of the measured J_{sc} values (in μA/cm^2) with the theoretical values making a normalization, that is: we scaled all the theoretical J_{sc} values imposing that for each lamp, at the maximum illuminance level, the calculated J_{sc} value be equal to the measured one. The results are shown in Fig. 7. For all the modules the trend is similar: with decreasing the illuminance the measured value decreases more rapidly than the theoretical one. The difference between the calculated and the measured value is higher at lower light intensities: this could indicate a dependence of the IPCE on the lightening conditions, in particular our results should evidence a IPCE worsening at lower light intensities, already reported for DSC [23].

4.2. Mixed natural and artificial light conditions

The results reported in the previous sections have been obtained under the only artificial light, with white-painted diffusing walls and at a very short distance between the source and the modules. In view of obtaining information on the solar cells efficacy as low power generators for indoor low consumption electronic devices, a more realistic condition has been tested. The I–V characteristics of two PV modules put in vertical position, in a real room exposed to a mixed daylight and artificial illumination have been monitored along one day. The chosen modules were the Si–μsph and the DSC, which in the previous reported experiments

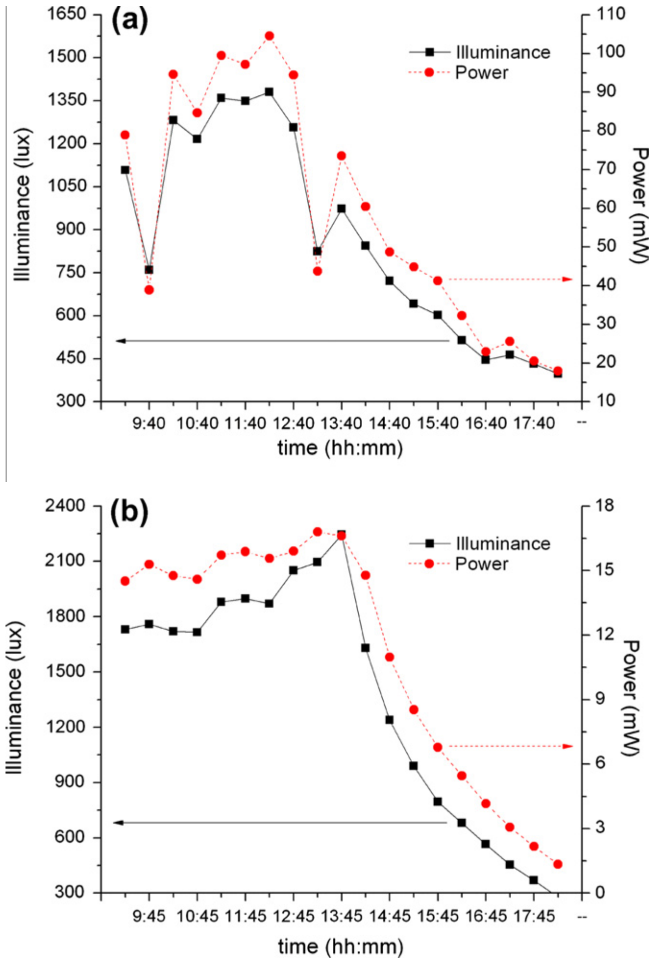

Fig. 8. Mixed natural/artificial illuminance values and related generated power for two different PV modules: (a) Si–μsph and (b) DSC.

have resulted to be the best performing examples of third generation PV modules. In Fig. 8 the maximum power values at the different time of the day, together with the respective measured illuminance level have been reported for the two modules. The experiments were performed in an April and a September day respectively for Si microspheres and DSC modules, in mean conditions of solar irradiance for the town of Torino, which is located in the North of Italy. The peak at 13.00 h for Si–μsph module is a shadow effect related to the sun illumination in the room wall. The maximum obtainable power for Si-usph has been reached at 12.10 and was of 104 mW, while for DSC it was of 16 mW, at 13.15. Furthermore, from the data it is possible to evaluate the energy which should have been obtainable with the two modules in the two examined days, assuming to work always in maximum power conditions, and neglecting the energy generated in the dark hours (with only the artificial light contribution). With the Si–μsph the obtainable energy value is of 2024 J, while with DSC the obtainable energy value is of 383 J. These results evidence the high variability of the obtainable electrical power and its dependence on time, which is one of the biggest disadvantages of photovoltaics for indoor applications, and also the low quantity of produced energy. Nevertheless they demonstrate the possibility of using both the modules for low power wireless applications such as, for instance, remote sensors, distributed controls and alarm systems, whose power requirements can be as low as some tenths of mW [17].

5. Conclusions

Commercially available photovoltaic modules based on completely different physical and chemical concepts, from semiconducting amorphous *p*–*i*–*n* junctions to photoelectrochemical cells based on TiO_2 nano-particles, to semiconducting polymers, to crystalline silicon micro-spheres have been measured under artificial light conditions using an appositely designed experimental set-up. The Si–μsph and the CIGS behavior is strongly reduced – at the same illuminance level – when fluorescent lamps are used instead of halogen or incandescent light sources. Organic and DSC modules do not present strong decrease in their performances under fluorescent tubes.

Si–μsph and DSC modules have been measured in a more realistic situation of mixed daylight and artificial illumination, and both have demonstrated to be usable for low-power wireless devices. The best performances have been obtained with Si-micro-spheres, with a maximum power of more than 200 mW under artificial light with white-painted diffusing walls and at 40 cm of distance between the source and the modules.

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