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SPECTRAL CHARACTERIZATION OF SOLAR CELLS FOR INDOOR WIRELESS SENSOR NODES

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Abstract: A standardized characterization method for solar cells is only available for outdoor use. For the supply of wireless sensor nodes with energy harvesting also indoor applications are of interest. Without comparable values it is difficult to select the proper cell for defined environmental conditions. Therefore it is necessary to compare them individually to be able to make a selection. The work presented here shows a characterization of solar cells according to their spectral behavior. For this investigation a test structure with a monochromator, different light sources, source measure units and instruments for measuring intensity and spectra have been combined. The measurements help to select the best solar cell for indoor energy harvesting applications.

Keywords: Solar Cell Characterization, Indoor Energy Harvesting, Wireless Sensor Nodes

1. INTRODUCTION

Modern sensor systems enable the acquirement of data in many different and complex fields. They are used for home automation, ambient assisted living, monitoring of production sites, environmental monitoring and many more. With a network of such systems it becomes possible to monitor a widespread area or a high number of objects (or both). This helps to gather information about the state of function of the monitored structure, to surveil defined parameters or to react to and control different procedures. With the integration of embedded systems in the recent years single sensor nodes became equipped with wireless communication parts. This simplifies the collection of data and allows the control of a large number of nodes with reduced effort. There are multiple solutions for the communication, like wireless personal area networks (WPAN) or protocols which are still in the standardization process or already standardized like ISA100 [1] or wirelessHART [2]. Those communication strategies also care for a reduction of the amount of data and an efficient routing strategy.

A problem that still exists is the energy supply of those sensor nodes. If the data cable is avoided by radio communication the power cable should also be removed. It can be replaced by a battery, but this would not be a sustainable solution. It causes toxic waste and depending on the system to supply it will have a short lifetime. This results in enhanced maintenance effort, especially in networks with a large number of nodes. A better way to supply wireless sensor systems is energy harvesting. This means the use of ambient non-electrical energy which is converted to electrical to supply an electronic system. Depending on the environmental conditions different sources with different energetic intensities can be available. For outdoor applications wind or solar radiation offer an opportunity. For indoor use the energy yield from a solar cell is much lower. Other solutions must be taken into consideration.

2. INDOOR APPLICATIONS

Figure 1 gives an overview about exemplary energy sources with their typical energy density which are conceivable for indoor use. It shows that for this field of application different solutions are feasible, as the values are in a equal range. The decision which source should be preferred depends on the environmental conditions and the allowed size of the transducer. This process is also influenced by the time per day when the source is available and the consumption of the system which needs to be supplied. For thermal energy a temperature gradient is required, which may be available in the night, when there is a higher difference between indoor and outdoor temperature. For vibrational energy a source is required which is active long enough. A quantity which is typically available indoors is light, either sunlight through windows or artificial light. As the energy yield from this source scales with the size of the transducer and different solar cells are budget-friendly available, this is often the preferred source.

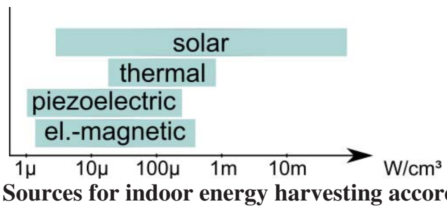

Figure 1 - Sources for indoor energy harvesting according to their power output [3][4][5].

3. CHARACTERIZATION OF SOLAR CELLS

For the design process of energy harvesting systems using solar cells different parameters have to be considered. The energy output depends on the intensity of light, the spectrum, the material and the size. Those characteristics need to be investigated to find the optimal cell for a wireless sensor node (WSN). For outdoor applications a standardized protocol to test and compare different modules is available [6], for indoor usage it is still missing.

The challenge of fitting the appropriate solar cell to the application is to have a cell that can handle the intensity and spectrum of the available light. As no standard test is available for this by now, cells qualified for a defined system need to be examined individually to predict the energy output and enable an electronics design.

Figure 2 shows the equivalent circuit diagram (two-diode) for a solar cell, which can be used to model and determine the behaviour of a cell with the two loss resistances. The series resistance is equal to the connection of of the module, the parallel resistance conforms to the surface recombination processes.

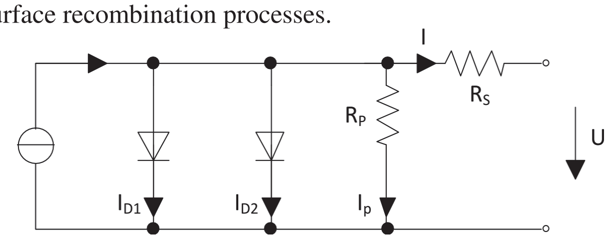

Figure 2 - Equivalent circuit diagram of a solar cell

Using the single diode model, which is more easy to handle and accurate enough for investigations ignoring the cell temperature the current and the voltage from a solar cell can be derived from the shockley-equation [7, p. 44]:

$$I_D = I_0 e^{\frac{U_D}{U_T}-1} \tag{1}$$

with a nonzero cutoff current

$$I_0 = I_{SC} e^{\frac{U_{OC}}{U_T}} \tag{2}$$

and

$$U_{OC} = U_T \cdot \ln(\frac{I_{ph}}{I_0} + 1) \tag{3}$$

where,

U_T	= thermal voltage
U_{OC}	= open circuit voltage
I_{SC}	= short circuit current
I_{ph}	= photocurrent.

The characteristic curve is shown in figure 3. It shows that the point where the power output reaches its maximum is independent from I_{SC} and U_{OC}. The correlation between these values and the maximal power that the cell can deliver can be described with the fill-factor *FF*:

$$FF = \frac{I_{MPP} \cdot U_{MPP}}{I_{SC} \cdot U_{OC}} = \frac{P_{MPP}}{P_{\max}} \tag{4}$$

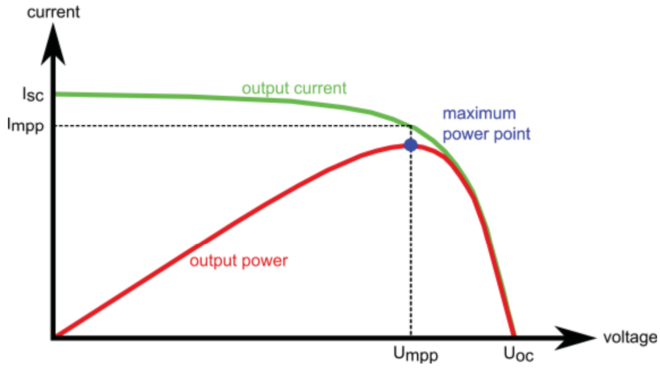

Figure 3 - I-V and power curve of the solar cell with maximum power point

The efficiency of the solar cell depends on the spectrum and the intensity of the irradiance $E_{e\lambda}$ and the area A which is being illuminated, taking into consideration that the illumination is wavelength dependent [8]:

$$\eta = \frac{P_{MPP}}{E_{e\lambda} \cdot A} = \frac{P_{MPP}}{\int_0^\infty \Phi_{p\lambda} \frac{hc}{\lambda} d\lambda} \tag{5}$$

Therefore the Wavelength must be considered for the characterization of the cells.

4. SPECTRAL BEHAVIOR

Different types of solar cells can react to the same illumination with a different energy output. It depends on the material and thereby the absorption coefficients for which wavelength the cell is sensitive. As for solar energy harvesting applications it is necessary to select cells which have an optimal size (concerning costs and and performance) it becomes important to know this behavior. The spectral sensitivity can be expressed as [7, p. 67]:

$$S(\lambda) = \frac{|j_{SC}(\lambda)|}{E(\lambda)} \tag{6}$$

which compares the short-circuit current density $j_{SC}(\lambda)$ to the wavelength-dependent irradiance $E(\lambda)$. With the knowledge of this parameter it is possible to determine the external quantum collection efficiency, which describes the number of charge carriers leaving the solar cell according to the number of photons that impinge on the cells surface [7, p. 54]:

$$Q_{ext}(\lambda) = S(\lambda)\frac{hc}{q\lambda} \tag{7}$$

It is in contrast to the internal quantum collection efficiency

$$Q_{\text{int}}(\lambda) = \frac{Q_{ext}(\lambda)}{1 - R(\lambda)} \tag{8}$$

with the reflection coefficient $R(\lambda)$ that considers only the part of the light that goes into the cell but not the part which is reflected by the coating [7, p. 54]. In the case considered here we like to measure the performance of a whole solar cell and this is why the external quantum efficiency is preferred.

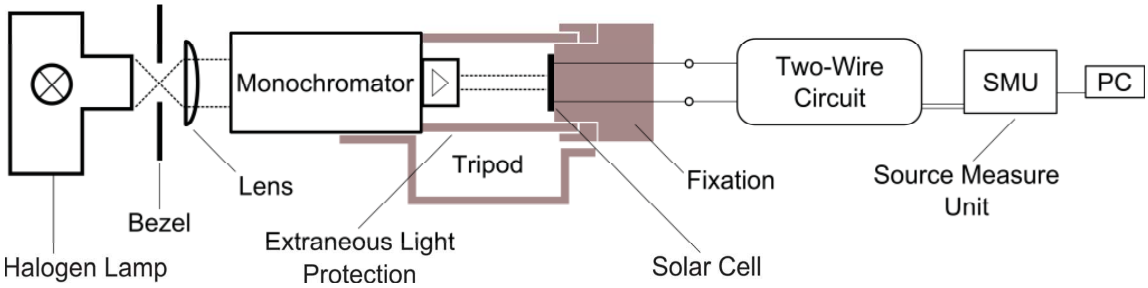

Figure 4 - Measurement setup for the determination of the spectral behavior of solar cells.

The measurement setup to determine these values for different solar cells is shown in figure 4. A monochromator splits focused light from a halogen lamp and produces light with a defined wavelength. Different solar cells have been fixed with a bracket and covered from ambient light. The test cell itself has been connected with a two-wire circuit to a source measurement unit (SMU). The test procedure is given by a pc, which controls and reads the measurement. As the halogen lamp works with a light source which is also wavelength dependent and therefore the output from the monochromator varies in intensity, the result has to be normalized to be comparable regarding the illumination.

For the measurement a small but constant area of the solar cell has been lighted. The area has been the same for all cells. Between two measurements the system must reach its steady state, therefore a time delay is necessary among two steps of a sweep. Furthermore the dark current must be determined and subtracted from the short circuit current in the measurement. The temperature has been monitored to make sure it keeps constant, as with increasing temperature the power output decreases. Overall it is recommended to normalize every result in order to avoid errors from different spectra and light intensities.

Table 1 gives an overview about the tested solar cells. They are all commercially available. Although all cells have different sizes and numbers of segments, the tested area has been kept constant at *0.75 cm²*. Most of them are intended for indoor use. For a comparison also one for outdoor use has been investigated. The cutoff current has been measured and subtracted from the Measurement.

The results are shown in figure 5, a-d, with short circuit current, spectral sensitivity, output power and quantum efficiency. The short circuit current in figure 5-a shows the reactions to excitations with different wavelengths. The SC6 (and to a lesser extend the SC4 also) is obviously sensitive to the short wavelength part of the near infrared light (IR-A). The other cells share the operating range of visible light. One reason for the importance of normalization for this kind of measurement can be seen in figure 5-c. As one might expect from 5-a the output power of the SC6, with respect to the voltage, should also be above all the others. Figure 5-c shows the maximum output power (power at MPP) of each cell with the SC4 being far on top. This occurs if no normalization for the spectral behavior of source and sample has been made. The monochromator itself has a spectral dependency which needs to be corrected. 5-a is an uncorrected graph showing that the output power of the monochromator has a maximum around a wavelength of *1 μm* which strongly influences the measurement. Only if this error is corrected, comparable values like in 5-c can be achieved. The SC2 generates only a very small output current and has not been considered in 5-b to 5-d furthermore. The figures 5-b and 5-c show the spectral sensitivity and the external quantum efficiency of the cells, both normalized. It can be seen that the SC4 performs best overall, followed by the SC6. The SC1 and SC5 are two cells fabricated the same way with just the size and thereby the number of segments as difference. The larger cell achieved inferior results in both measurements. This can be led back to shading effects, as for the larger cell it was not possible to illuminate all of the segments.

5. CONCLUSION

Currently there is no standardization for the power output of solar cells indoors as there is outdoors with the AM spectra. This leads to the problem that it is not possible to select a proper cell for energy harvesting solutions just from the datasheet. It depends on the spectral behaviour, the dimensions, light sources and structure at most. As detailed information about these values normally is not available, it becomes necessary to characterize the cells individually. Therefore the spectral behaviour has been investigated in this work. The sensitivity and efficiency across the wavelength have been measured and compared with each other. With this Information the best solar cell for a defined

Label	No. of Segments	Active Area in *cm²*	Type	Application	Measured Cutoff Current in *nA*
SC1	8	25.36	amorphous	indoor	30
SC2	6	20.23	amorphous	outdoor	83
SC3	8	3.56	amorphous	indoor	8
SC4	2	14.76	amorphous	indoor	30
SC5	4	2.34	amorphous	indoor	30
SC6	3	1.08	crystalline	indoor	250

Table 1 - Overview about the tested solar cells

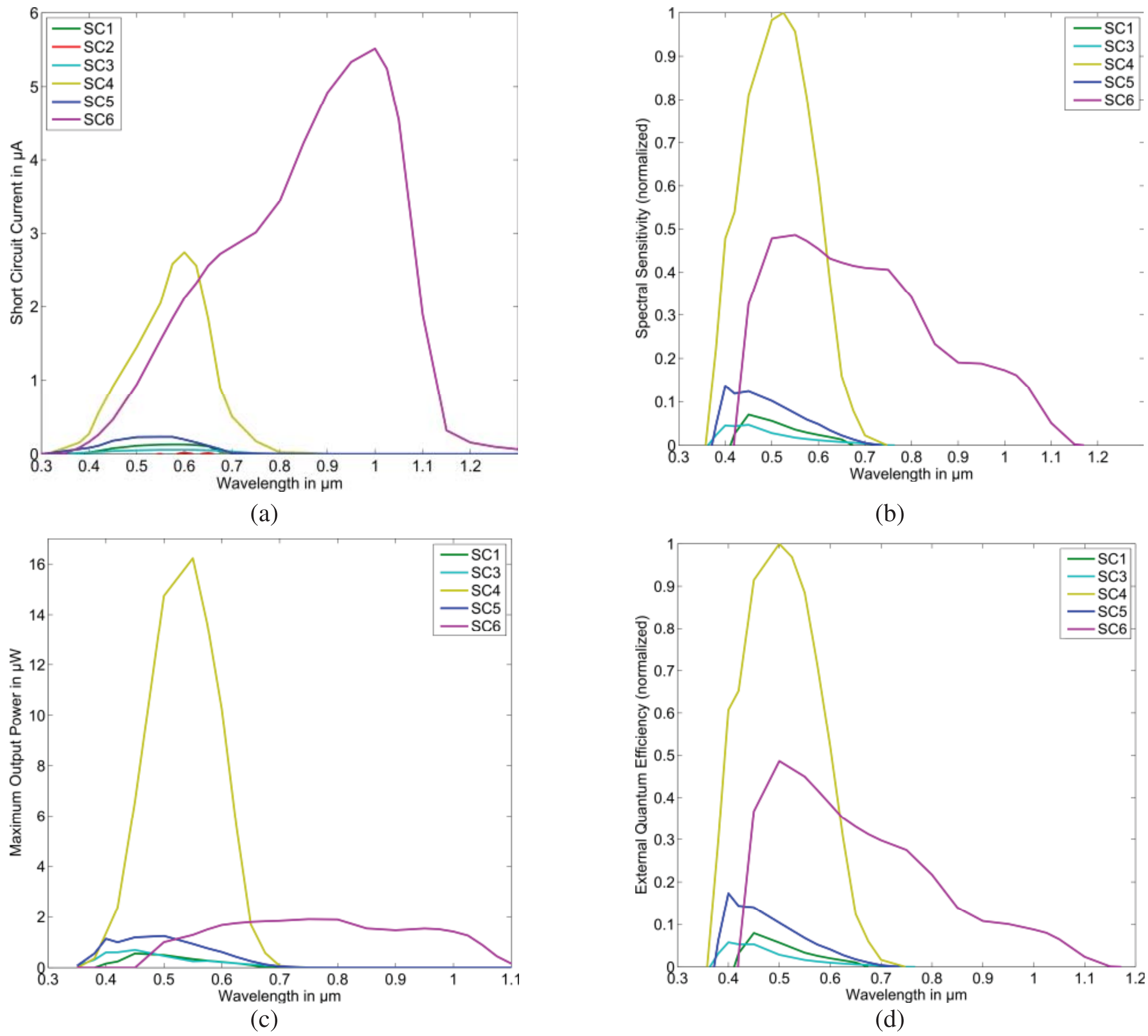

Figure 5 - Spectral investigation of 6 different solar cells: (a) Wavelength-dependent short circuit current; (b) normalized spectral sensitivity; (c) output power according to the wavelength; (d) normalized external quantum efficiency.

application can be selected. It can also be decided which light source is to prefer, if there is more than one and the spectrum is known.

6. OUTLOOK

This work will be extended with an investigation about the influence of illumination to the behaviour of the cell in future. With this information it becomes possible to compare sources which do not fit the spectrum of a solar cell but have a high power output, to other sources which have a ideal spectrum adaption but a lower power output.

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