BENTHAM

Technical Note

Spectral Characterisation of Photovoltaic Devices

Photovoltaic Characterisation

Overview

This technical note provides an overview of photovoltaic (PV) devices and the spectral characterisation techniques used in the evaluation of their efficacy in the goal of harnessing a maximum of energy from the sun and artificial sources of light.

Photovoltaic Devices

This term refers to a number of types of devices, designed for the conversion of light to electricity, via the photovoltaic effect.

The history of the use of PV devices began with their use as the energy source for satellites in orbit. This application indeed continues in parallel with the use of PV devices as a renewable energy source and in consumer devices, albeit with differing terms of reference.

Whilst high budget space applications place more of an accent on energy production efficiency, with cost a secondary consideration, the use of PV for renewable energy and consumer products, is very much focussed on cost reduction.

Other than the (often significant) cost in manufacturing and installing PV devices, the energy generated is essentially free, and widely available. It is for this reason that solar energy is increasingly being looked at as a viable source for our global energy requirements, and for use in consumer devices.

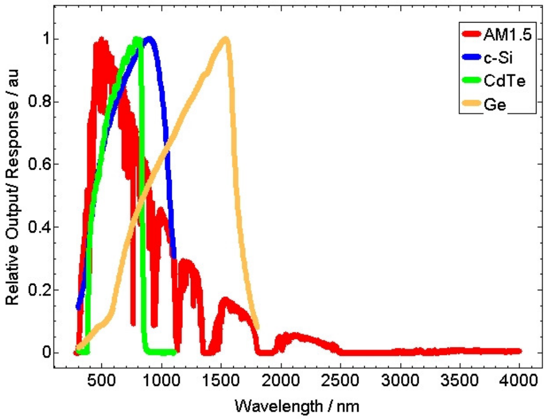
The photovoltaic effect involves an incident photon of light liberating an electron from a material to be available to provide work in an external circuit. The efficiency of this conversion process and the wavelengths of light at which this process occurs vary greatly with the different materials used.

The light source in question is invariably the sun, although certain consumer devices may be made for indoor use. In any case, the source of light being exploited shall typically have a broad emission spectrum- it is a question, therefore, of designing PV devices which have a wavelength response which covers as much as possible of this broad output, and converts as much light as possible into electricity.

In practice, photovoltaic devices respond only to a restricted range of wavelengths, as can be seen here, where the response of a few typical devices are compared with the AM1.5G reference spectrum.

AM1.5G is a standard approximation to the output of the sun. Note, however, that the range of response is not the sole consideration in the evaluation of a PV device, but also the efficiency of this conversion process.

These parameters are quantified by measurement of the spectral responsivity of the device, and the determination of energy conversion efficiency.



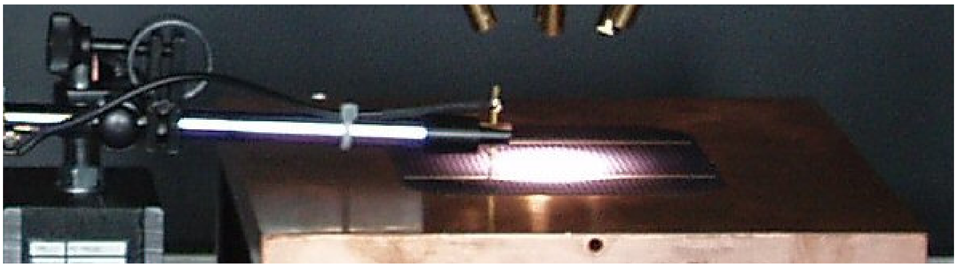
AM1.5G reference spectrum against the wavelength responsivity of a selection of current PV devices

Photovoltaic Device Materials

PV device types are generally classified in three generations.

The first generation devices, adopting the technological advances of the microelectronics industry, are based on single-junction crystalline silicon which currently remains the default material for PV devices.
The material used is of very high quality, yielding high efficiencies, but at a significant cost. Due to the relatively poor light absorption of this material, devices need to be several hundred microns thick which represents a significant raw material cost. Furthermore, expensive manufacture techniques are required in the processing of crystalline silicone.

As a push for cheaper PV devices, is encountered, recourse is being made to second generation devices, which benefit from thin-film technology. Since these materials have good light absorption, up to a factor 100 less material is required, with an immediate material saving. In addition to this, process techniques are much less complex, and therefore cheaper, and significantly in some instances can be processed at low temperatures opening up the possibility of creating devices based on a flexible plastic substrate for example. Alas, however, nothing is free, these devices are also characterised by a poorer material quality which results in losses of light generated electrons in the structure, and a corresponding reduction in efficiency.

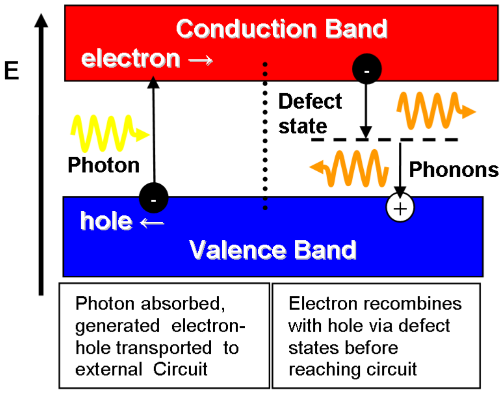


Third generation devices encompass a vast panoply of technologies, aimed at improving the efficiency of existing devices, or introducing different materials and material structures. These include multiple junction devices, which combine materials of different spectral response to cover better the range emitted from the source; mirror or lens based concentrators to increase the level of light exposure of the device, up to the equivalent of hundreds of suns; organic polymer based devices and dye-sensitised devices, both based on very low cost technology and available on flexible substrates.

Standard Testing Procedures

International standards are published to provide guidelines for the testing required of photovoltaic devices, for example IEC 60904-1 describes I-V testing, IEC 60904-3 the determination of module efficiency, IEC 60904-8 single junction device relative spectral response measurements and ASTM E2236 multi-junction spectral response measurements.

In essence, these standards specify the conditions of the measurements of PV devices, requiring for example the use solar simulator approximating AM1.5G at a level of 1000 Wm^{-2}, and controlled sample temperature.



Photon absorbed, generated electron-hole transported to external Circuit

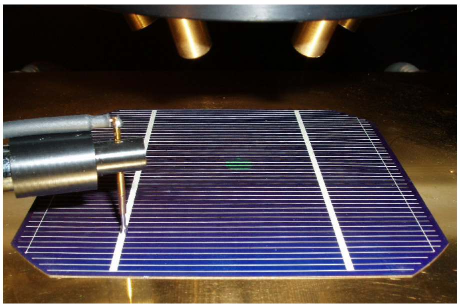
Electron recombines with hole via defect states before reaching circuit

Solar Simulator

The use of the solar simulator physically places the device in true operating conditions, and is related particularly to material quality. In poorer quality material, where the crystal structure is defective, there exists traps and defects to which generated carriers are lost. Light from the solar simulator generates a large number of carriers in the material which can pump defects and traps, ensuring that the carriers generated by the probe beam are not thus lost, compared to measurements with the probe without solar bias.

The use of solar simulator in the case of multi-junction devices has an additional function. Multi-junction devices comprise junctions of material of different spectral response in series; the signal from a given junction is only passed to the external circuit providing that the other junctions are conducting, and have a sufficient number of free carriers.

It should be ensured that none of the other junctions are current limiting, leading one to think that the junction under test is poorly performing. To this end, the non-tested junctions should be bias to a sufficient level to ensure that they do not limit the current flowing through the device.



Temperature control is also an important consideration since as temperature rises, the crystalline properties of the devices are modified (one obtains with device heating a red shift in the response), and its efficiency can decrease as more energy is lost to phonons in the lattice.

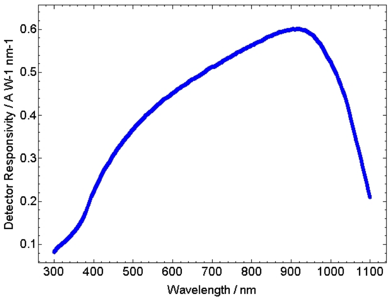
The essential measurement quantities are as follows:-

Spectral response

The spectral response (A W^{-1}) of a PV device provides information on the physics at play in the global device, ie. takes into account not only the material, but also the reflectance and transmittance of the device.

This quantity is measured with the device illuminated by a source simulating the sun, termed one sun bias, to simulate the true circumstances of device operation, and with the device temperature controlled, typically to 20°C.

This measurement is performed by shining a monochromatic probe beam onto the sample and registering the photocurrent generated as a function of wavelength. The probe is first characterised, using a device of known responsivity (A W^{-1}) to determine the power in the beam, and from here, measuring the photocurrent generated as a function of wavelength from the device under test, its responsivity can be determined.



External Quantum Efficiency

The external quantum efficiency (EQE) is defined as the number of electrons provided o the external circuit per photon incident on the device, and is directly obtained from the spectral response measurement by the following argument:-

The number, **n**, of electrons generated by the device, **$n=(It/e)$**, where **I** is the generated current, **t** time and **e** the charge of the electron

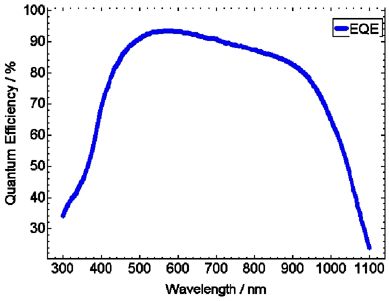
The number, **m**, of photons, incident on the sample, **$m= Pt/E_v$**, where **P** is the power in the beam, **t** time, and **E_v** the photon energy

The quantum efficiency, **η**, is defined as,

$$\eta = 100*n/m = 100x(It/e)/(Pt/E_v) = 100x(I/P)*(E_v/e)$$

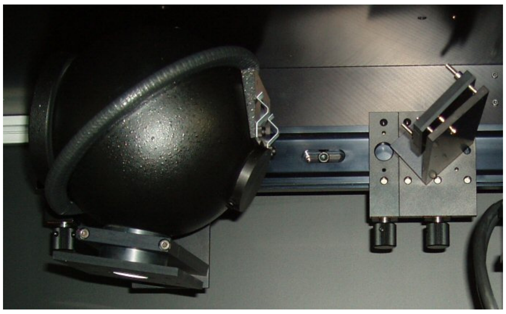
$$\eta= 100xSx(hc/e)*(1/) \approx 1.24x10^5xS/ \lambda \ (nm)$$

Where **S** is the spectral responsivity.



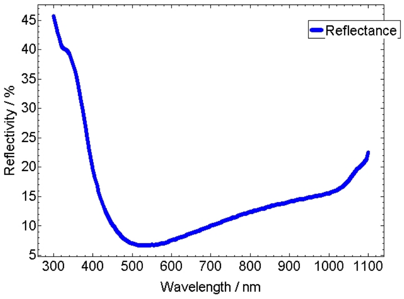
EQE can therefore be determined directly from a measurement of the spectral response.

Reflectance, Transmittance and Internal Quantum Efficiency



In an ideal world, all photons reaching a PV device are transmitted only to the active region where the conversion process occurs.

Due to the refractive index of the materials used, light shall be reflected from the front surface of the device (to mitigate which anti-reflection coatings are applied), and in the case of thin- film devices, light may be transmitted.



The total reflectance (diffuse and specular), and the (diffuse) transmittance, of the device can be measured with the aid of an integrating sphere.

In addition to providing a manner of determining device IQE (see below), this measurement also permits the characterisation of anti– reflection coatings.

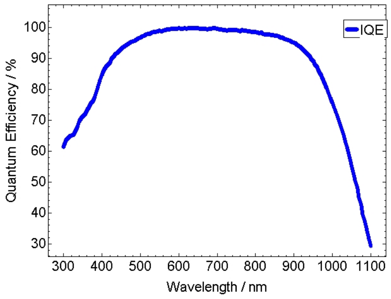
Internal Quantum Efficiency

Based on the above measurements of reflectance and transmittance, the EQE can be modified to take into account the actual reflectance and transmittance of a device permits the determination of the number of photons reaching the active region to obtain a better understanding of the operation thereof.

This is simply expressed as:

IQE = EQE/ (1-R-T)

Where **R** is the reflectance, and **T** the transmittance of the sample.



Fluorescent Material Characterisation

The process of fluorescence may either be used in two principle cases.

1. The overall performance of a given PV device may be enhanced the by moving emission of light to wavelengths where the device has a higher responsivity.

2. In the case of fluorescent collectors, combining fluorescent dyes, and solar cells in the implementation of BIPV (building integrated photovoltaics) technology, for example in tinted windows.

Fluorescent materials are typically excited in the UV and emit photons in the lower energy visible-IR region.

A system comprising and excitation and emission monochromator can be used to characterise these parameters; exciting the material at a given wavelength, one can determine the emission spectrum, and vice versa.