Differences of silicon photodiode spectral reflectance among the same batch

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Photodiode's reflectance plays an important role regarding the relation between responsivity and the incident flux. In this work we analyze how the spectral reflectance changes among photodiodes from the same manufacturer and batch and how the reflectance of three standard photodiodes has drifted during six years. The results show that the reflectance changes from diode to diode within the same batch and also show that the reflectance of photodiodes changes on time. This ageing is spectrally dependent.

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Silicon photodiodes are more sensitive and quicker than thermal detectors. For these reasons silicon photodiodes are used to maintain scales of spectral responsivity in the spectral range (300 nm – 1000 nm) in many National Laboratories [1-5].

The spectral responsivity of a photodiode depends on the reflectance and the internal quantum efficiency, so a good approach to determine responsivity is to know both reflectance and internal quantum efficiency. Because of that, in this work we present a study about the reflectance of silicon photodiodes, with two goals: to study the variability of reflectance among photodiodes from a single batch, and to study the reflectance aging of some silicon photodiodes used as standards during six years. In some radiometric applications, the reflectance of individual photodiodes plays an important role because they have to match to a pair or be minimized or maximized, as it is the case for silicon trap radiometers[6, 7]. The ageing of silicon photodiodes has been studied by several authors and all of them looked at the stability of the internal quantum efficiency[8, 9] rather than at the reflectance.

To approach the first objective, we restrict the study to a single manufacturer, because the reflectance is linked to the structure and thickness of the passivation layer. We chose photodiodes from Hamamatsu, because they are the most stable and are used in many National Laboratories. Furthermore we have used photodiodes from just one batch to avoid as much as possible changes in the oxide thickness which in turn produces different reflectance values.

To achieve the second goal, the aging of photodiodes, we have measured the reflectance of three silicon photodiodes, from the same manufacturer, which are used to maintain the scale of spectral responsivity of Institute for Applied Physics (CSIC).

The results show that we have an outstanding change between the reflectance of the photodiodes of the same batch, which indicates that it is necessary to measure the reflectance of every individual photodiode if the accurate reflectance knowledge is needed.

The study of reflectance of standard detectors shows that aging occurs in a different way for every one of them, so, again, it is necessary to measure the reflectance of every individual photodiode to have a precise knowledge on the evolution of its reflectance.

When the radiation impinges on a detector, different physical processes happen. Part of incident radiation is reflected by the sensitive surface, and the rest passes to the interior of detector, which can be partially or totally absorbed. The response of the photodetector is related to the amount of absorbed power, but for evaluating the incident power it is necessary to know the absorbed, the reflected and the transmitted ones.

If the photodiode's response to optical radiation is its short circuit current, the total photodiode response can be written as:

$$I = \left(1 - \rho(\lambda)\right)\eta\,(\lambda)\frac{\lambda q}{hc}\phi\ , \tag{1}$$

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where I is the dark current, $\eta(\lambda)$ is the internal quantum efficiency, which indicates the number of electrons produced by each absorbed photon, q is the electrical charge of the electron, h is the Planck constant , c is the light velocity , ϕ is the radiant flux, λ is the wavelength and $\rho(\lambda)$ is the photodiode's reflectance. From equation (1) the responsivity can be obtained as

$$R=\frac{I-I_0}{\phi}=\left(1-\rho(\lambda)\right)\eta(\lambda)\frac{\lambda q}{hc}\ . \tag{2}$$

This equation tells us that the responsivity depends on the wavelength of the incident radiation, directly and via the reflectance of the surface and the quantum efficiency. Then, the responsivity will be known if the reflectance and internal quantum efficiency are known at every wavelength. For this reason, the measurement of the photodiodes' reflectance is presented in this work as a previous step to know the responsivity.

Looking at equation (2) and bearing in mind the layered structure of silicon photodiodes and the high refraction index values, it is noticeable to remark that photodiode's response notably depends on the angle of incidence and the polarization state of the incoming radiation[6,7,10].

To measure the photodiodes´ reflectance we have arranged an experimental setup as shown in Fig.1. Kripton, He-Ne and He-Cd lasers have been used in this setup as radiation (sources).

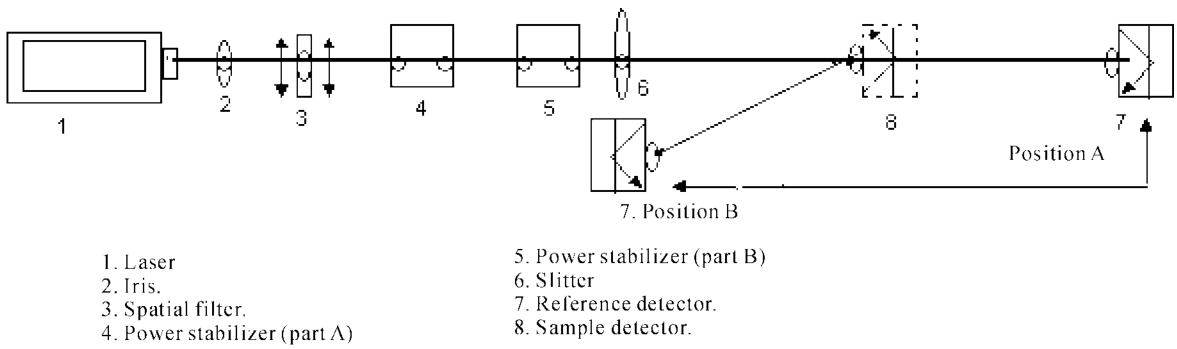

Fig.1 Experimental setup for measuring reflectance.

The linearly polarized laser beam is spatially filtered and power stabilized. Afterward the beam goes through a shutter that can be controlled via a PC (Personal Computer). The shutter is used to block the laser beam to measure the photodiode dark response that is subtracted to every photodiode's reading. Placing a photodiode in position A, the incident power is recorded.

To measure the power reflected by the photodiode to be tested, we introduce it in the laser beam with an angle of incidence about 3º and move the reference photodiode to position B.

We remark that the photodiode to be tested is half way between the shutter and position A of the reference detector, so that the beam seen by the reference detector runs the same way in both cases, assuming specular reflection at the photodiode's front surface. Furthermore, the reference detector is used at normal incidence in both cases. It is important that the incidence angle over the sample photodiode is small, because the reflectance changes with the incidence angle, as mentioned before. If we record the ratio between the signal of the reference detector in position B (reflected power) and the signal in position A (incident power), we will get the spectral reflectance of the photodiode under test.

By this method we have measured the spectral reflectance of one set of ten photodiodes from the same manufacturer and batch and of another set of three photodiodes (from the same manufacturer) used to maintain the spectral responsivity scale at the Institute for Applied Physics (CSIC).

Measurements are done at wavelengths of 441.8 nm (He-Cd), 568.2 nm (Kr), 632.8 nm (He-Ne) and 647.1 nm (Kr). A typical uncertainty value for this kind of measurement in this laboratory is 0.15 % [1].

Fig.2 shows the reflectance measured for photodiodes 1 to 5. Photodiodes 1 and 2 have almost the same behavior, and something similar happens to photodiodes 3 and 4. Only photodiode 5 seems to behave in a more different way.

Reflectance values measured for photodiodes 6 to 10 are shown in Fig.3. Photodiodes 7, 8 and 9 have almost the same behavior up to the wavelength of 632.8 nm from which they differentiate. In general spectral reflectance values of all the photodiodes studied are closer in the range of 441.8 nm - 632.8 nm. Quantitatively, the maximum difference is about 3 % at 441.8 nm and about 7 % at 647.1 nm. The second goal of this work is to study aging effect over the reflectance of silicon photodiodes used to maintain responsivity scales.

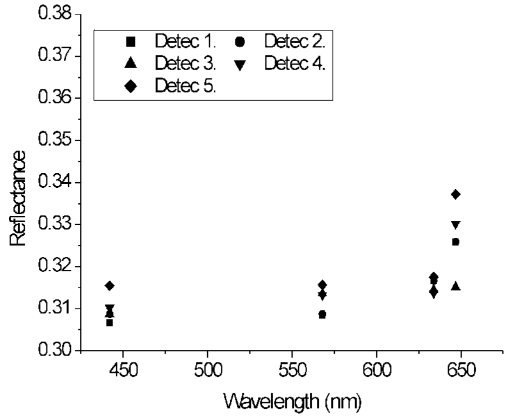

Fig.2 Measured reflectance of No.1-5 photodiodes

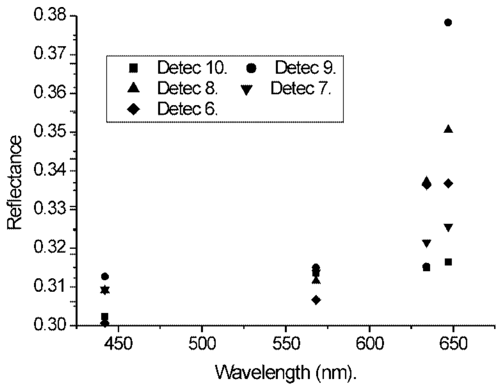

Fig.3 Measured reflectance of No.6-10 photodiodes

Fig.4 shows the reflectance values measured in this work for standard detectors Ciri, Dss 01 and Dss 02, whose spectral responsivity was calibrated six years ago for the first time.

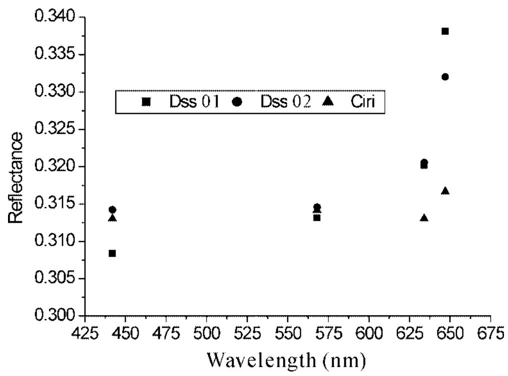

Fig.4 Measured reflectance of standard detectors.

Difference between the old spectral reflectance values and the present ones, for these photodiodes can be seen in Fig.5.

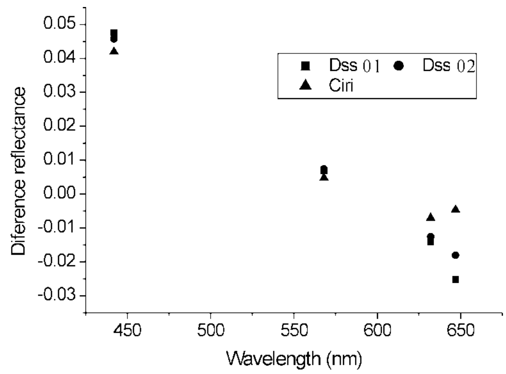

Fig.5 Difference between previous spectral reflectance values and values of this work

The same tendency can be observed for the three photodiodes: at short wavelengths the reflectance difference is positive, i.e. the photodiode's reflectance decreases, while at long wavelengths the reflectance difference is negative, which means that the photodiode reflectance increases.

Furthermore, the relative spectral reflectance change is larger at short wavelengths (5%) than at long wavelengths. It also seems that the tendency is spectrally monotonous.

If it is assumed that the change in reflectance is related just to a thickness change of the silicon oxide passivation layer [5,7,11], an increase of about 2 nm over 30 nm would be needed approximately, to explain such a change. This type of change in the silicon oxide layer has not been referred in the literature (to the knowledge of the authors) and it is not likely to be produced since the detectors have been always kept at room temperature in dry environments. Therefore another mechanism must be likely responsible for this behavior.

At present state of the art of technology, the reflectance of silicon photodiodes changes from item to item within the same batch. Therefore in high accuracy applications where the reflectance plays an important role as in the case of trap detectors for radiometric measurements, it is necessary to measure the reflectance of single element to select them for matching or minimum reflectance.

Ageing of silicon photodiodes is related not only to internal quantum efficiency as it has been considered by other authors, but also to spectral reflectance changes as it has been shown in this work.

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