Measuring the reflectance and the internal quantum efficiency of silicon and InGaAs/InP photodiodes in near infrared range. - art...

Article *in* Proceedings of SPIE - The International Society for Optical Engineering · February 2008

DOI: 10.1117/12.763885

Joaquin Campos
Spanish National Research Council

Alicia Pons
Spanish National Research Council

Measuring the reflectance and the internal quantum efficiency of silicon and InGaAs/InP photodiodes in near infrared range.

Ana Luz Muñoz Zurita [1)], Joaquin Campos Acosta [2)]
Alexandre S. Shcherbakov [1)], Alicia Pons Aglio[2)].

1) Department of Optics, National Institute for
Astrophysics, Optics, and Electronics (INAOE),
A.P. 51 y 216, Puebla, Pue., 72000, Mexico. Fax/Tel. 52 (222) 247 2940.
E-mail: alex@inaoep.mx, azurita@inaoep.mx

2) Department of Metrology, Institute for Applied Physics (CSIC), Serrano 144, Madrid, 28006, Spain. Phone: 34 91 561 8806, ext. 326; Fax: 34 91 411 7651, ext. 206;
E-mail: joaquin.campos@ifa.cetef.csic.es, alicia.pons@ifa.cetef.csic.es

1. Abstract.

At the present time, silicon and InGaAs/InP photodetectors from different manufactures have rather low level of noise, a good uniformity of the surface response as well as a wide dynamic range and linearity. For these reasons they are exploited in the instruments for measuring optical radiation within the near infrared range 800-1600 nm. Furthermore, the silicon and InGaAs/InP photodetectors are used for maintaining the scales of spectral responsitivity in the above-listed spectral range in many laboratories. Due to the last application, we presented our studies of the reflectance and the internal quantum efficiency inherent in silicon and InGaAs/InP photodiodes from different manufactures.

Both the reflectance and the internal quantum efficiency determine the photodiode spectral responsivity, which is the radiometric characteristic of interest in the fields where these devices can be used for optical radiation measurements. The responsivity will be known if both the reflectance and the internal quantum efficiency are known at every wavelength We have measured the reflectance of three silicon photodiodes and three InGaAs/InP photodiodes that were practically used to maintain scale of the spectral responsivity in the Institute for Applied Physics (CSIC). The results obtained show that we have an outstanding change between the reflectance of the photodiodes of the same set, which indicates that its necessary to measure the reflectance of every individual photodiode if an accurate reflectance knowledge is needed, its necessary to measure the reflectance of every individual photodiode to have a precise knowledge on the evolution of its reflectance.

Key words: reflectance, near infrared range, photodiodes.

2. Introduction.

The photodetectors are chosen as the first device of interest because of their simple structure, and since their analysis is a natural extension, almost an example, of our discussion of p-n diodes. Whereas the field of photodetectors goes way beyond that of semiconductor photodetectors, we restrict ourselves here to such devices. We will discuss P-i-N diodes, which are also referred to as photovoltaic detectors, photoconductors, solar cells and metal-semiconductor-metal photodetectors. The distinction between the different devices is somewhat artificial since many similarities exist between these devices but it enables to clearly separate the difference in structure, principle of operation and purpose of the devices.[2]

Optical Components and Materials V, edited by Michel J. F. Digonnet, Shibin Jiang, John W. Glesener, J. Christopher Dries
Proc. of SPIE Vol. 6890, 68900P, (2008) · 0277-786X/08/$18 · doi: 10.1117/12.763885

To understand the operation of photodetectors is important the next parameters: Speed of a photodiode is characterized by the bandwidth of the frequency response or the Full Width Half Maximum (FWHM) of the pulse response, Responsivity is measured as the ratio of current in the detector to the incident optical power to the device, the Sensitivity is defined as the minimal input power that can still be detected which as a first approximation is defined as the optical power which generates an electrical signal equal to that due to noise of the diode.[3]

Its sensitivity is independent of temperature for each of the three pairs of wavelength intervals considered in the sensor design.[4] One related characteristic is the quantum efficiency of the detector which is the ratio of the number of electron-hole pairs which contribute to current to the number of incident photons.

When the light radiation impinges on a detector, a few various physical processes occur; a part of the incident light is reflected by the sensitive surface, while the rest passes inside the detector, where can be partially, because of losses due to absorption, converted into an electronic signal. The response of each photodetector is conditioned by a quantity of the converted light power, but for evaluating the incident light power one had to know the ratios between the reflected, absorbed, and converted portions.

An InGaAs/InP-photodetector is a photodiode based on a p-n or p-i-n structure. In similar structure, there is a region, which can be denominated as the depleted or exhausted region. An electric field sweeps the generated charge carriers and produces an electrical current in this region. In addition charge generated outside that region also contributes to the photocurrent. Thus, the total photodiode response I can be written as [5]:

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

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

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

This equation shows that the responsivity depends on the wavelength of the incident light by three ways, directly, via the reflectance of a surface, and through the quantum efficiency. This equation indicates also, that the responsivity will be known if both the reflectance and the internal quantum efficiency are known at every wavelength [6,7].

For this reason, measuring the reflectance of photodiodes is presented in this work as a preliminary step to finding the responsivity. It is seen from equation 2 that the photodiode response depends on a set of parameters inherent in the incident light like the spectral distribution, polarization, modulation of frequency, angle of incidence, and radiant power. Then, the response is determined by such characteristics of photodetector as the material refraction index and the structure of diode as well as by some environmental factors, for example, by the temperature.

3. Measured of reflectance of silicon photodiodes.

To measure the reflectance of photodiodes, we have arranged an experimental setup as shown in figure 1. Kripton laser, He-Ne and He-Cd lasers have been used in this setup.

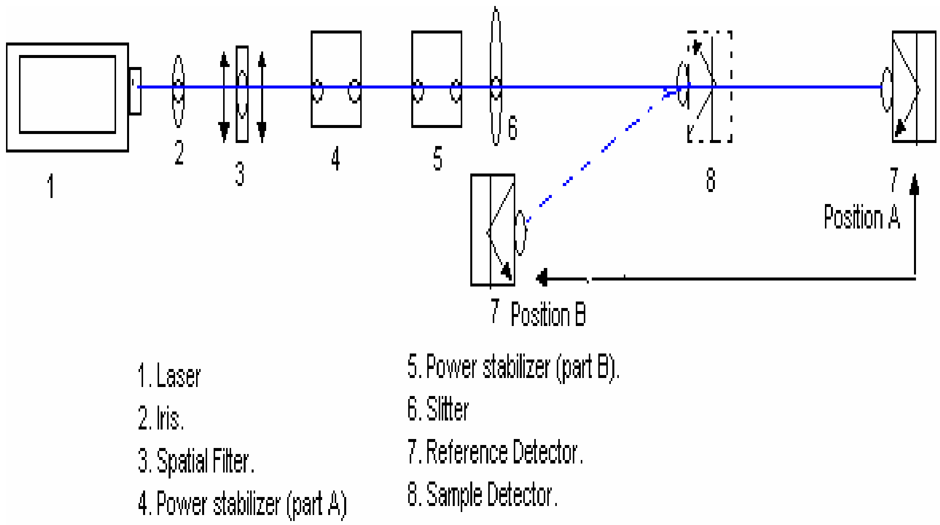


Figure 1
Experimental setup for the measured reflectance.

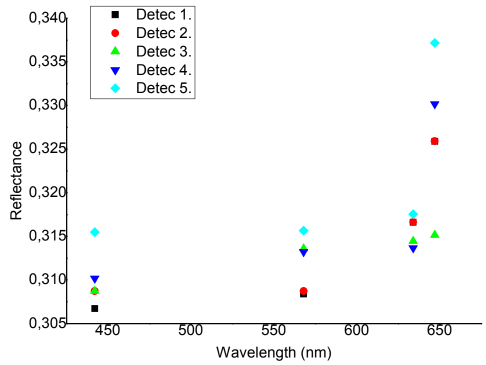
We have a laser beam spatially filtered that goes through the power stabilizer (with 2 parts A and B) whose function is indicated its name.After that the beam goes through a shutter with a diaphragm which we can manipulate using the PC (Personal Computer). The shutter is used to block the laser beam to measure the photodiode dark response, that is substracted to every photodiode reading.

This way we measure the power incident on the photodiode to be tested. 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. Let remark that the photodiode to be tested is half way between the shutter and position A of reference detector, so that the beam seen by the reference detector runs the same way in both cases. Furthermore, reference detector is used at normal incidence in both cases.

It is important that the incidence angle over the sample photodiode be small, because the reflectance changes with the incidence angle. If we make 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.

4. Interpretation of results about measured of reflectance of silicon photodiodes.

In the figures 2, 3 and 4 are shown some experimental results obtained in the laboratory of radiometry of the institute of Applied Physics (CSIC) that can be interpreted by the light of that exposed in this paper. The figure 1 represent the lineality of the photodiodes (A and B) of the same model (Epitaxx, InGaAs/InP,3 mm of diameter). It is seen that both photodiodes is saturated in the same point, but that they show curved of different lineality.



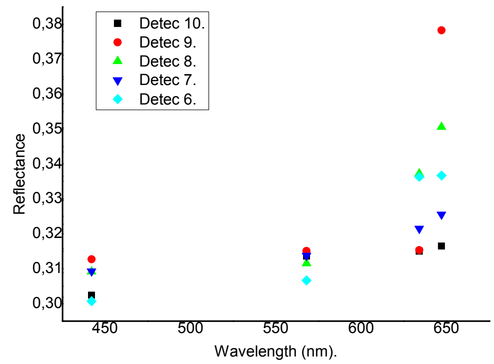


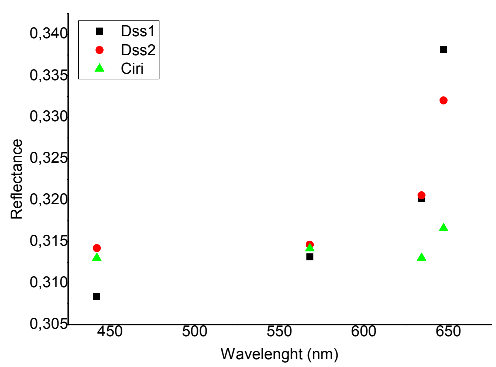
Figure 2
Reflectance of detectors 1-5.

Figure 3
Reflectance of detectors 6-10.

In Figure 2 we can observe the reflectance of the detectors 1-5. Detector 1 and 2 have almost the same behavior, and something similar happens with detectors 3 and 4. Only detector 5 seems to behave in a more different way. In Figure 3, the numbers 7,8 and 9 have almost the same behavior until the wavelength of 632.8 nm where number 7 differs abruptly.

In general photodetectors have little difference in the wavelength of 441.8 nm and 632.8 nm, but a larger one at 647.1 nm. The same thing can be seen in the Figure 2 for detectors 1-5. They are much more alike at 441.8 nm and 632.8 nm and differ more at 647.1 nm.

To quantity the difference in reflectance among detectors we can say that this difference is about 7% at 647.1 nm and only 3% at 441.8 nm approximately.



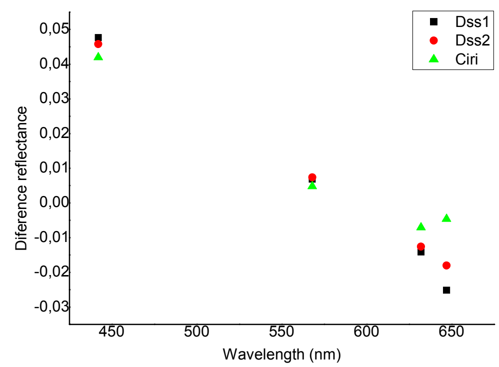


Figure 4
Reflectance of detectors standard

Figure 5
Difference between previous measure and new measure.

In the Figure 4 we can see the reflectance values measured in this work for standard detectors Ciri, Dss01 and Dss02. In the Figure 5 we can see to reflectance difference between the old reflectance values and the present one, for those three detectors. We can see that the maximum reflectance value for these standard (old) detectors is at short wavelength while the maximum for the new detectors is at long wavelength. We can also see that the reflectance of standard detectors has diminished from 0.39 to 0.34 approximately.

Analyzing the difference between the previous values and the new values (Figure 5) we can observe that at short wavelength the reflectance difference is larger (5%) and positive; i.e. the photodiode's reflectance has decreased, while at long wavelengths the reflectance difference is smaller (2%) and negative, which means that the photodiode reflectance has increased.

4. Measured of reflectance of InGaAs/InP photodiodes.

To realize our experiments related to measuring the reflectance of InGaAs/InP photodiodes we have arranged the experimental set-up presented in Figure 6

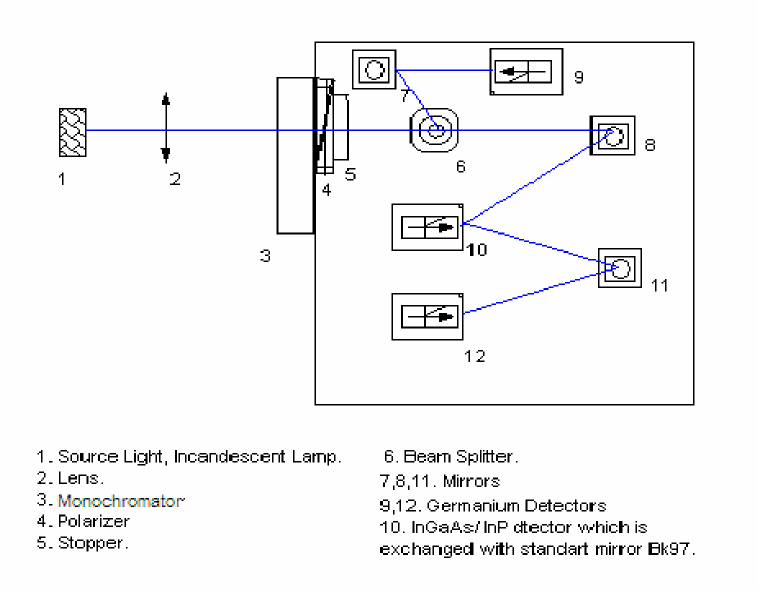


Figure 6
Experimental set-up for measuring the reflectance InGaAs/InP photodiodes.

We have exploited an incandescence lamp is the source of white light imaged at the input slit of the monochromator. This lamp was able to cover the spectral range from 800 to 1600 nm and had appropriate blocking filters for second – order wavelengths. After the monochromator, we had placed a linear polarizer and a beam splitter, which serves to monitor temporal fluctuations of light power. A germanium photodiode was used as the monitoring reference photodetector.

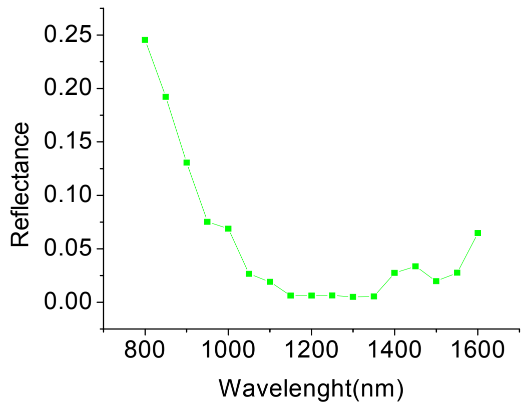
The experimental set-up included an optical system of mirrors, which consists of two arms. An upper arm (see mirror 7 and germanium photodiode 9) realized monitoring temporal fluctuations of light power. A bottom arm (see mirrors 8, 11; InGaAs/InP-photodiode 10, and and germanium photodiode 12) formed an image of the monochromator's exit slit on the sensitive surfaces of photodiodes.The angle of incidence was equal to 7.4 °, which was accepted as the normal incidence in this train of measurements. The method of measurement consists in comparing the response from a germanium photodiode to the radiation reflected by the InGaAs/InP photodiode with the response from an aluminium standard mirror whose reflectance is known, so that [3]:

$$\rho(\lambda) = \frac{I_p(\lambda)}{I_m(\lambda)} \rho_m(\lambda) \ . \qquad (15)$$

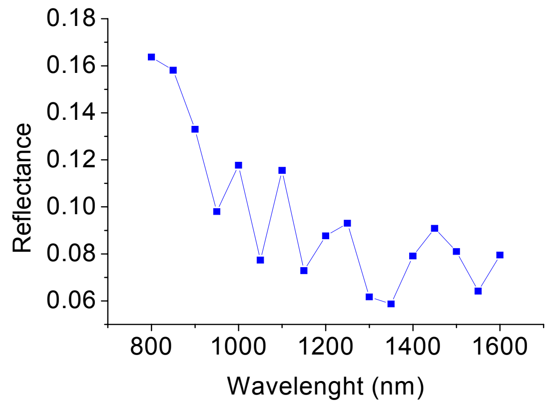
Here, $I_p(\lambda)$ is the response to the light reflected by the InGaAs/InP, $I_m(\lambda)$ is the response to the light reflected by the mirror, and $\rho_m(\lambda)$ is the reflectance of a standard mirror. With this method we have measured the reflectance of photodiodes from different manufacturers. One part of detectors had a round aperture of 5 mm in diameter and the other part had a rectangular aperture of 8 x 8 mm.

5. Results about measuring the reflectance of InGaAs/InP Photodiodes.

Figure 7 illustrates spectral dependences of the reflectance, which had been obtained from photodetectors belonging to three different manufacturers. The grade of light polarization at the output the monochromator was different with varying the wavelength. Figures 7a and 7b are related to the detectors with round aperture.



(a)



(b)

Figure 7
Detector with a round aperture with the diameter of 5mm.

It follows from figures 7(a) and 7 (b) that the reflectance of such detectors has a minimum in an area of 1000 – 1600 nm, and they both are related to a structure of layers providing maximal responses in the spectral interval of mayor utility of these detectors in near IR optics communication. The first photodiode, see figure 7 (a), whose reflectance was minimized, is more efficient that the second one, see figure 7 (b).

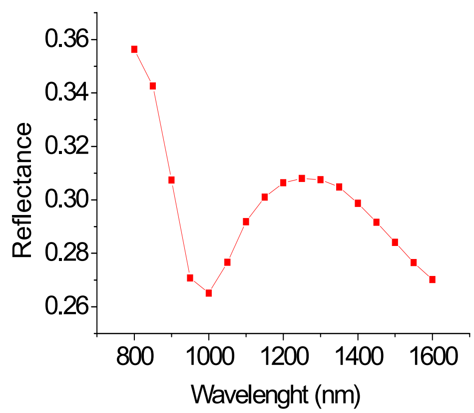


Figure 8
Detector with a rectangular aperture of 8 x 8mm.

Figure 8 is associated with a photodiode with rectangular aperture. One can see that this plot presents the other spectrum of reflectance. In this case the reflectance has two minima at 1000 nm and 1600nm, but the reflectance has a maximum between these minima. This photodiode is older than previous ones, and it was produced by the other manufacturer. One can remark that may be it was produced without good enough control, because the structure of layers on the sensitive surface modifies the reflectance.

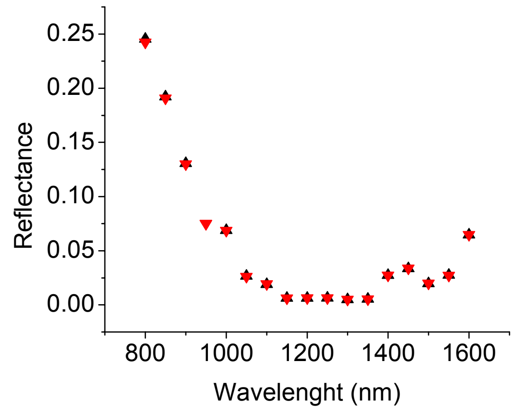


Figure 9
Spectrum of reflectance for photodiodes 1 and 4.

Figure 9 presents the spectrum of reflectance for photodiodes 1 and 4, which belong to the same manufacturer. The reflectance was measured with linearly polarized and non-polarized lights, and these pair of measurements gives quite similar results. In fact, the difference was equal to approximately 2%.

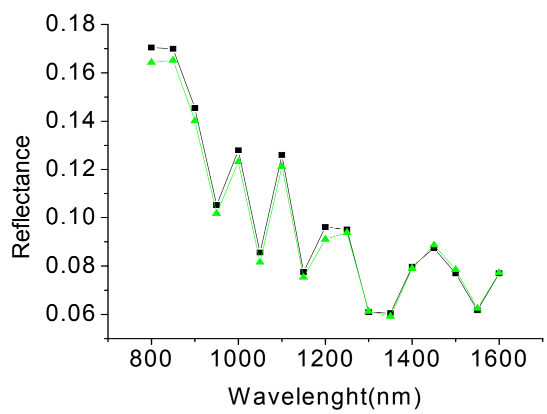


Figure 10
Spectrum of reflectance of photodiodes 2 and 5.

The same results are depicted for the photodiodes 2 and 5, belonged the second manufacturer. It is important that the results do not depend on the polarization state of the incident light when the angle of incidence is smaller 10 angular degrees.

6. Conclusions.

In the case of photodiodes of Silicon, the reflectance was measured in different wavelength is in the range of 400 nm and 650 nm, analyzing the difference between the previous values and the new values (Figure 5) we can observe that at short wavelength the reflectance difference is larger (5%) and positive; i.e. the photodiode's reflectance has decreased, while at long wavelengths the reflectance difference is smaller (2%) and negative, which means that the photodiode reflectance has increased.

In the case of photodiodes of InGaAs/InP, the reflectance was measured with linearly polarized and non-polarized lights, and these pair of measurements gives quite similar results. In fact, the difference was equal to approximately 2%. The same results are depicted for the photodiodes 2 and 5, by the second manufacturer. It is important that the results do not depend on the polarization state of the incident light when the angle of incidence is smaller 10 angular degrees.

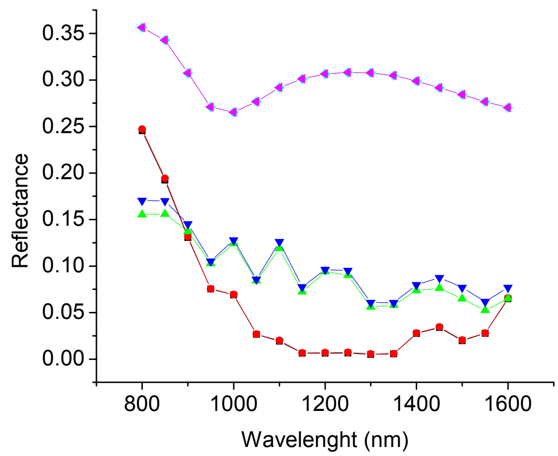


Figure11.
Spectrum of reflectance of photodiodes 1-6.

Finally in the figure 11 presents all spectrums of reflectance for photodiodes 1-6, with linearly polarized and non polarized lights and is possible to see the different behavior of the photodiodes in the near infrared wavelength.

In fact in this work we are studying the behavior of the photodetectors in the near infrared with the linearly polarized and non polarized lights in the case of the polarized lights the angle of incidence is smaller 10 angular degrees and is possible observed we don't have changes in the behavior of the reflectance.

7. References.

1. J. Campos, P. Corredera, A. Pons, A. Corróns J. L. Fontecha. *"Reflectance dependencies of silicon trap detectors".* ,IOP Metrología, **35**, 455-460,(1998).
2. P Corredera, M L Hernanz, M González-Herráez and J Campos *"Anomalous non-linear behaviour of InGaAs photodiodes with overfilled illumination"* IOP Metrología **40**, S181-S184,(2003).
3. P Corredera, M L Hernanz, J Campos, A Corróns, A Pons and J L Fontecha.. *"Comparison between absolute thermal radiometers at wavelengths of 1300 nm and 1550 nm"* IOP Metrología. **37**. 237-247, (2000).
4. J.Castrellon, G.Paez, M.Strojnik. *"Radiometric análisis of a fiber optic temperatura sensor"* Opt.Eng, **41 (6)**,1255-1261 (2002).
5. R. Goebel, S. Yilmaz, R.Pello.*"Polarization dependence of trap detectors"*, IOP Metrología, **33**,207-213, (1996).
6. E.F.Zalewski, C.R.Duda, *"Silicon photodiode device with 100% external quantum efficiency"*. Appl.Opt.,**22**, 2867-2873, (1983).
7. J.M.Coutin, F.Chandoul, J.Bastie. "*Characterization of new trap detectors as transfer standards*". Proceedings of the 9th international conference on new developments and applications in optical radiometry.(2005).
8. A.L.Muñoz Zurita, J.Campos Acosta, A.Pons Aglio. A.S.Shcherbakov. *"Medida de la reflectancia de fotodiodos de InGaAs/InP".* Óptica Pura y Aplicada, **40(1)**, 105-109 (2007).