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QUANTUM EFFICIENCY DETERMINATION OF UNBIASED SILICON PHOTODIODE AND PHOTODIODE BASED TRAP DETECTORS

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Abstract. This work describes the determination of both internal and external quantum efficiency, QE, of unbiased silicon photodiodes (p^+-n) to be used as a light detection element in the trap detectors, which are in general used as the optical responsivity transfer standard. The internal QE values of silicon photodiodes and of trap detectors were calculated from experimentally measured responsivity and reflectance values with an uncertainty at the order of 10^{-3} and 10^{-4}%. By applying a QE model that is based on the photodiodes electrical parameters like recombination velocity, diffusion length, diffusion coefficient, absorption coefficient, etc. the internal QE values were extrapolated to 400-1100 nm range. The variations in reflectance and responsivity due to the surface non-homogeneities of photodiodes were also analysed and their effects on QE were calculated approximately at the order of 10^{-4}%.

1. INTRODUCTION

The quantum efficiency is defined as a degree of effectiveness of the incident radiant flux for producing measurable parameters like temperature, current, etc. in a detector [1]. Depending on the portion of light that takes part in formation of these effects, it can be defined either as internal QE or external QE. The internal QE for a photodiode is the number of electron hole pairs created per absorbed photons; whereas, the external QE is the number of number of electron hole pairs created per incident photons [1].

The QE is in general expressed as a function of one of the parameters like wavelength, absorption coefficient, frequency, *etc*. At a certain wavelength if the incident photons are completely absorbed and all the generated minority carriers contribute to the current, then the QE at that particular wavelength is said to be unity. Optical reflection losses, carrier recombinations, defects, passivating layer thickness, doping level, *etc.*, have been considered as the important parameters that cause the reduction of QE below the unity [2].

The silicon-based photodiodes generally have been produced in such a way that their internal QE is close to unity especially in the visible region of electromagnetic spectra [3]. However, due to the loss mechanisms mentioned above there expected to be some deflections from unity, which are called internal QE deficiency. In order to take these loss mechanisms into account and to calculate QE, some mathematical modes have been developed by Geist [4], Geist *et al*. [5], Gentile *et al*. [6], L.Kreinin *et al.* [7], N. Bordin *et al.* [8], Alejendro *et al.* [9]

In this work both the internal QE and the external QE of the silicon photodiodes were studied. Moreover, effects of the surface reflectance and responsivity non-homogeneities on the QE were analyzed.

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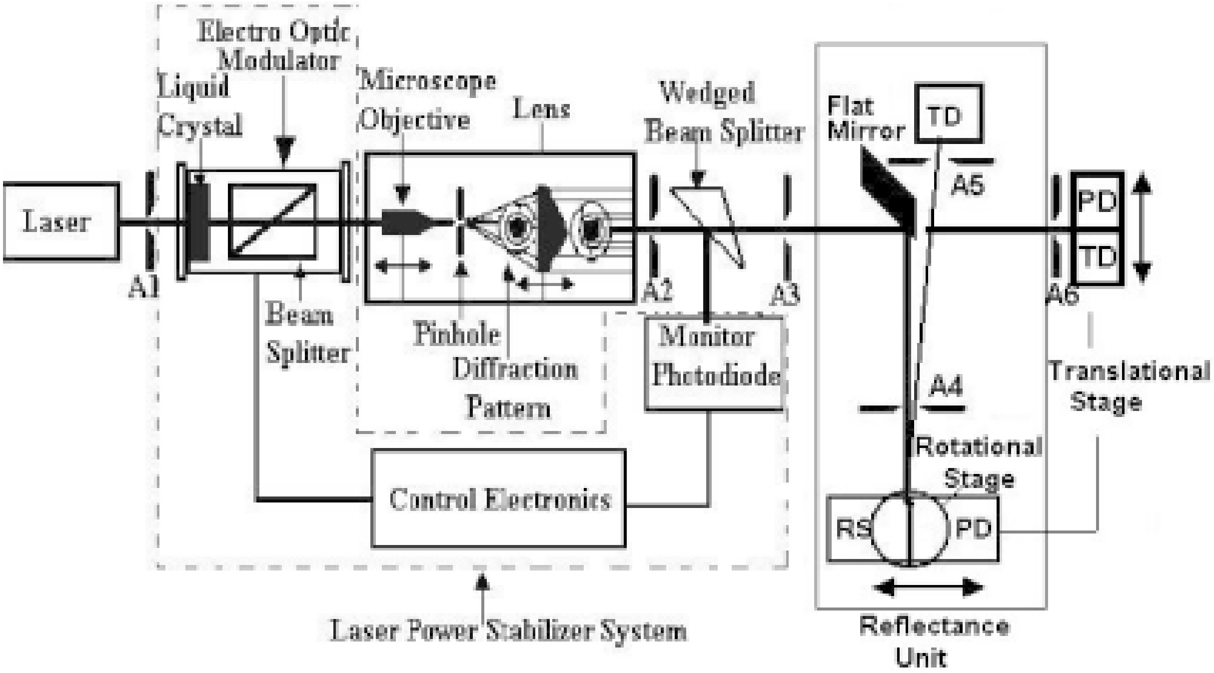

Fig. 1. Laser based responsivity and reflectance measurement set up.

2. QUANTUM EFFICIENCY

Incident radiant flux on a photodiode undergoes reflectance, absorbance and transmittance events. The percentage of the incident photons that contribute to photocurrent is defined as external QE and is given by: [1,9,10]

$$EQE(\lambda) = \frac{Rhc}{q\lambda}. \tag{1}$$

where R is the responsivity of a photodiode which is given as the measured current per incident radiation power, c is the velocity of light in vacuum, q is the electron charge, λ is the wavelength of light and h stands for the Planck's constant.

Some portion of light beam will be reflected from the photodiode surface. The percentage of contribution of remaining photons to photocurrent or to the reflectance ρ corrected external QE, which is called internal QE, is given as [1,9,10]:

$$IQE(\lambda) = \frac{Rhc}{q\lambda(1-\rho)} = \frac{EQE}{(1-\rho)}. \tag{2}$$

3. EXPERIMENTAL

The optical measurement set up shown in Fig. 1 was used to measure the responsivity, R of the silicon photodiodes. The main parameters of the set up are; laser source, and laser power stabilizer system (LPS) and detection system. Measurements were done using fixed He-Ne (632.8 nm) and tuneable Ar-Ion (488 and 514.5 nm) lasers. LPS system was used to compensate the fluctuations in the lasers output intensities. This system also has a spatial filter system which functions for generating a geometrically well-defined Gaussian beam to be incident on the photodiode. Using this system diameter of laser beams were adjusted to 3 mm ($1/e^2$ points) and the fluctuations in their power were reduced to approximately 0.006%.

The responsivity measurements of photodiodes and trap detectors are shown in the Fig. 2. Curve 1 shows experimental responsivity for the photodiode obtained by comparing with a reference standard whose responsivity is traceable to electrically substituted cryogenic radiometer system described in our previous works [11,12]. A reflectance unit was added to responsivity measurement system that enables us to measure the reflectance of photodiodes at the same laser wavelengths. In this system, the stabilized laser beam was aligned to incident a point close to the rim of a mirror so as to get the small angle between the incident and the reflected beam. This prevents the effects that can arise due to polarization dependence of reflectance [13]. The detector under measurement and the

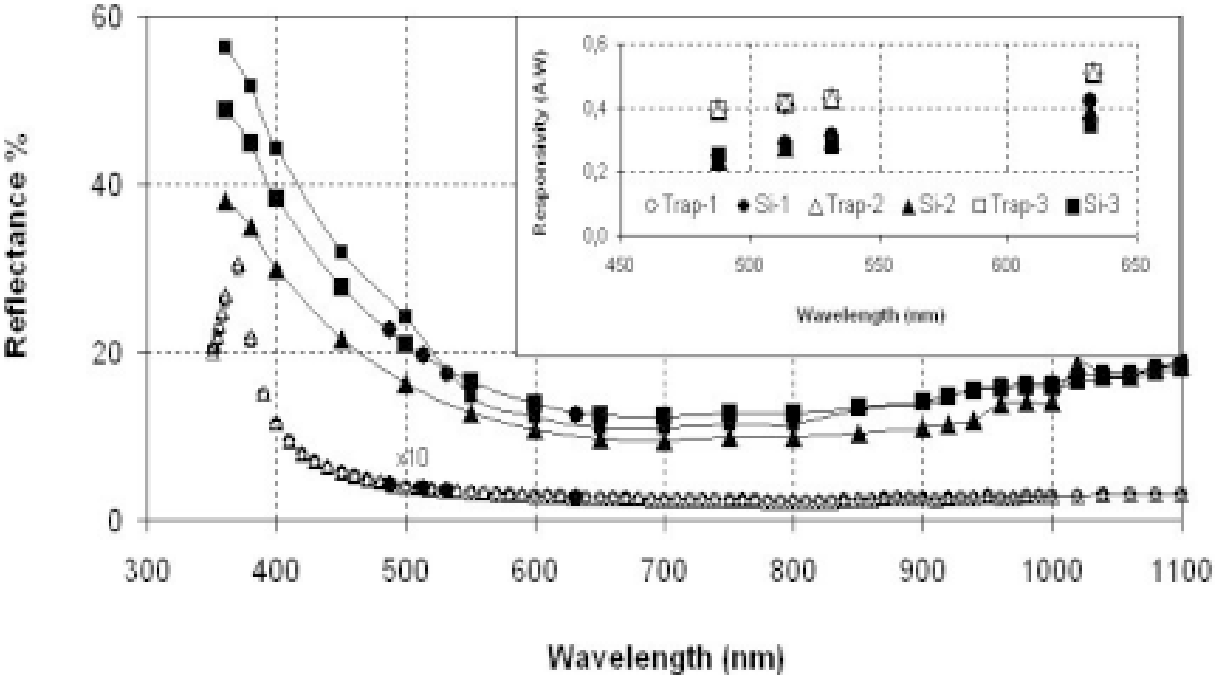

Fig. 2. Optical responsivity and reflectance values of silicon photodiode. Reflectance values of Si-trap are multiplied with 10 to display on the same graph.

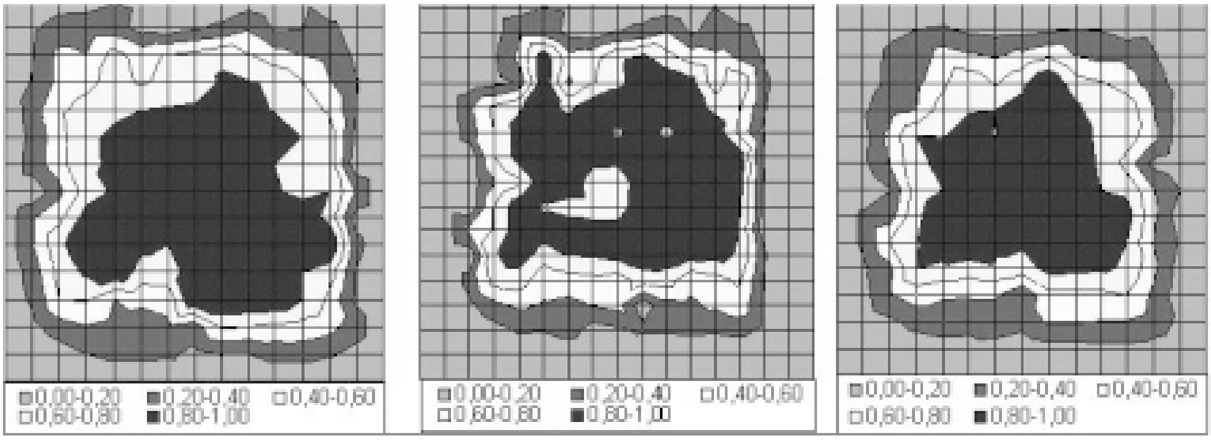

Fig.3. Variation of responsivity values over the surface of silicon photodiodes.

reference reflectance standard were placed on a rotating and translating stages respectively and the reflected beams were measured separately using silicon photodiode based trap detector. The measured reflectance values are shown in Fig. 2, Curve 2.

Substituting those values into Eq. (2) we get the internal QE values. The repeated measurements of responsivity and reflectance indicated that the uncertainty in the internal QE is of the order of 10^{-3} and 10^{-4}%. This variation has been related to the spatial non-uniformity of light source and detector active area (illuminated area). Since the internal QE measurements consist of simultaneous measurements of diode reflectance and spectral responsivity, the effects of surface non-uniformity on these parameters and thereby on QE were analyzed by measuring the spatial variation of photodiodes. In the responsivity measurement set up, Fig.1, the photodiodes were mounted on X-Y translation stage, which was driven by PC-controlled step motors. Using power stabilized He-Ne laser (632.8 nm) beam having spot size of 1.0 mm diameter, the spatial uniformities were investigated by scanning the surface of photodiodes with a step length of 1.0 mm. The spatial variations of about 10^{-4}% were observed within the 10 mm diameter on the surface of photodiodes, Fig. 3.

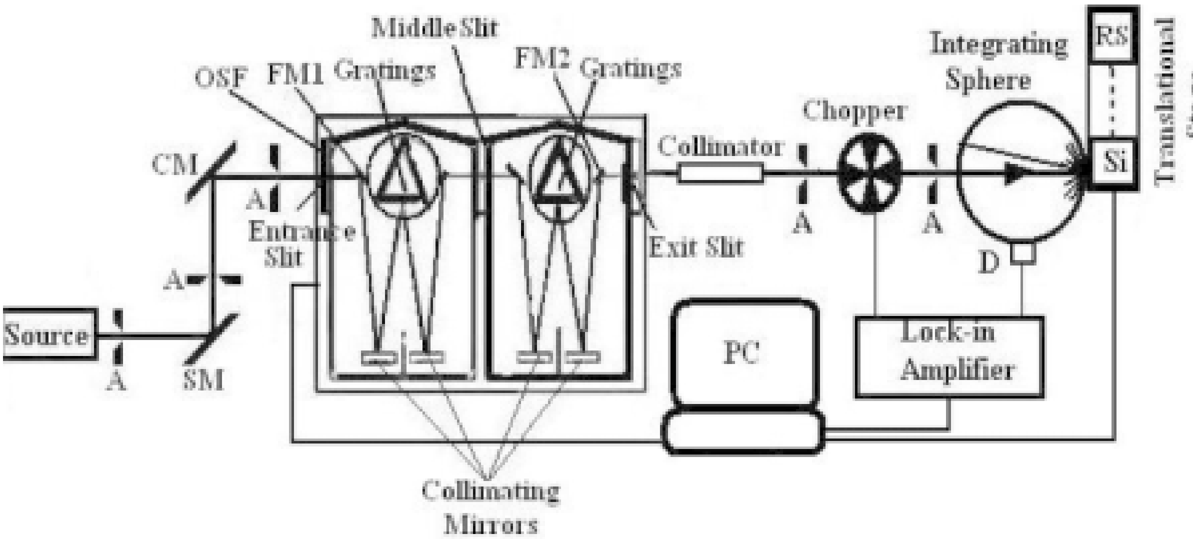

Fig. 4. Spectral reflectance measurement set up. A: Aperture, FM; Flat Mirror, SM: Spherical Mirror, CM: Cylindrical Mirror, OSF: Order Sorting Filter, D; Detector; Si: Silicon, RS; Reference Standard.

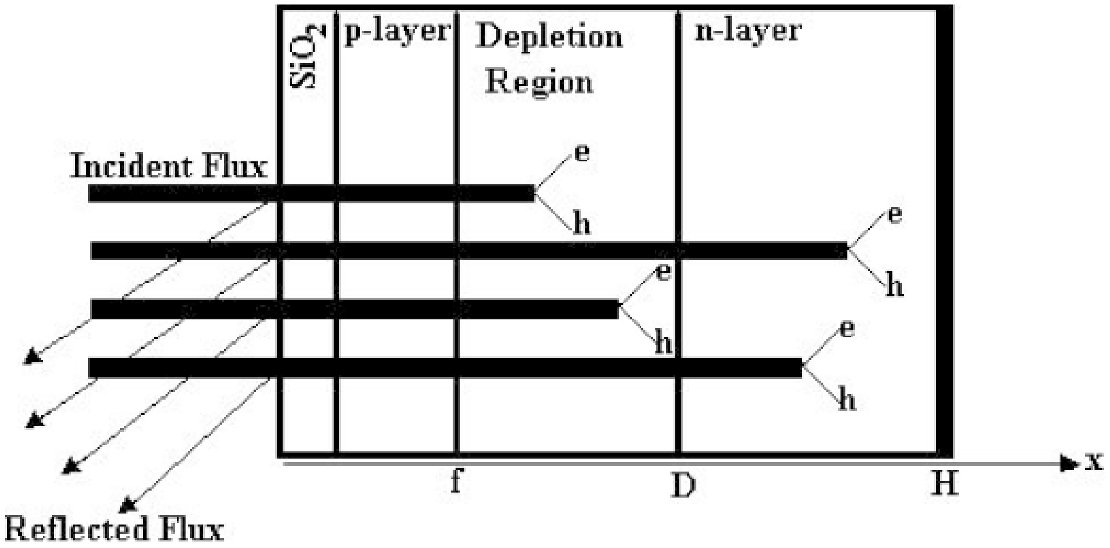

Fig. 5. Absorption and generation of electron hole pairs in silicon photodiode structure.

The QE values of a silicon photodiodes, which are the most widely used detector within the spectral range from 400 to 1100 nm, obtained in this way are limited to only certain laser wavelengths. The whole values within this range from 400 nm to 1100 nm were obtained by applying the model described in Section 4.

The surface reflectance looses of silicon photodiodes within the range from 400 nm to 1100 nm were measured using double monochromator system consisting of collimator, integrating sphere, lock in amplifier and detector system as shown in Fig. 4. As a light source a flat tungsten filament quartz halogen lamp was used and it was operated at a constant current mode, which kept the output from the lamp stable to within few tenths of a percent over a measurement period. The monochromatic beam emerged from monochromator system was collimated and directed to the photodiode surface and reference standard respectively. Reflected beams from the photodiode surface and reference standard were collected in the integrating sphere separately and these signals were recorded using silicon photodiode trap detector.

4. MODELING OF QUANTUM EFFICIENCY

In this work, we examined the internal QE of the photodiode whose structure as shown in Fig. 5 has thin p layer (p<<n). When a flux of photons incident on a photodiode, some portion of that flux undergoes reflection losses, the remaining part transmits through the oxide layer, which is deposited on the surface of photodiode for surface passivation, and is absorbed by silicon results in generation of electron hole minority carriers. To be able to express the photocurrent in the p-n photodiode drift and diffusion, current of carriers given in eqns.3 should be examined [14, 15]

$$J_p = pq\mu_p E - qD_p \frac{\mathrm{d}p_n}{\mathrm{d}x}, \tag{3a}$$

$$J_n = nq\mu_n E + qD_n \frac{\mathrm{d}n_p}{\mathrm{d}x}, \tag{3b}$$

where the first terms are drift currents which arise from electric field E at the space charge region, and second terms are diffusion currents due to concentration gradient of carriers, $D_{p,n}$ and $\mu_{p,n}$ are hole (electron) diffusion constant and mobility respectively.

The photon flux inside the photodiode varies exponentially with distance generate electron hole pairs. Some of these carriers undergo recombination and do not contribute to current. Thus, the variation of these carriers inside the photodiode, which is called continuity equation, are given as [14,15]

$$\begin{aligned}&\left[p(x,t+\mathrm{d}t)-p(x,t)\right]A\,\mathrm{d}x = \\ &\left[F_p(x)-F(x+\mathrm{d}x)\right]A\,\mathrm{d}t+\left(G_p-R_p\right)A\,\mathrm{d}x\,\mathrm{d}t,\end{aligned} \tag{4a}$$

$$\begin{aligned}&\left[n(x,t+\mathrm{d}t)-n(x,t)\right]A\,\mathrm{d}x = \\ &\left[F_n(x)-F_n(x+\mathrm{d}x)\right]A\,\mathrm{d}t+\left(G_n-R_n\right)A\,\mathrm{d}x\,\mathrm{d}t,\end{aligned} \tag{4b}$$

where the terms in the left hand side are time rate of change of carriers in Adx volume element, the first terms in the right hand side are the change in the photon flux, G and R are generation and recombination of carriers.

Using the relation between current density and photon flux for electron and holes $J_{n,p} = \pm qF$ and also substituting Eqs. (3a) and (3b) into Eqs. (4a) and (4b) we get the following equations.

$$\frac{\partial p_n}{\partial t} = D_p \frac{\partial^2 p_n}{\partial x^2} - E\mu_p \frac{\partial p_n}{\partial x} + G_p - R_p, \tag{5a}$$

$$\frac{\partial n_p}{\partial t} = D_n \frac{\partial^2 n_p}{\partial x^2} + E\mu_n \frac{\partial n_p}{\partial x} + G_n - R_n. \tag{5b}$$

Since the absorption depth depends on absorption coefficient, we assumed that below about 400 nm a negligible amount of photons could be absorbed in the thin p-region. Photons within 400-900 nm are almost absorbed in the depletion region where, due to build in field, approximately all the generated electron hole pairs contribute to the current and as a result internal QE is assumed to be unity. However, in the n-region due to recombination of carriers the internal QE is expected to deviate much from unity at higher wavelengths. In the light of these assumptions, we calculate internal QE by considering only the current due to minority carriers in the depletion region and n side of photodiode. By considering the electric field in the neutral n region as zero and also by taking into account only steady state condition, the first term in the left hand side of Eq. (5a) vanishes. Thus we have

$$D_p \frac{\partial^2 p_n}{\partial x^2} + G - R = 0, \tag{6}$$

The generation G and recombination R rate parameters in Eq. (6) were defined by considering that the generation rate of electron and hole pairs inside the photodiode in the both depletion and n regions vary exponentially as a function of absorption coefficient α as $G = (1 - \rho)F_0\alpha e^{-\alpha}$. Recombination rate in Si photodiode, which have indirect band gap, is defined by the local energy levels within the band. We used recombination rate defined by Hall, Read, and Shockley and made an assumption that trap energy level is at the mid gap, so for low injection we have $R = (p_n - p_{n0})/t_p$ [16,17]. Having defined the G and R parameters in Eq. (6) and the boundary conditions (a- the back surface recombination velocity is S_b and at $x=H$ it has the relation $S_b Dp_n = -D_p dp_n/dx$. b- there is no recombination in the p and depletion regions, then at $x=D$, $Dp_n=0$) the variations of minority carriers, Eq. (7) in n side of photodiode can easily be obtained with a simple mathematical algebra.

$$p_n - p_{n0} = \frac{\alpha(1-\rho)F_0\tau_p}{1-\alpha^2 L_p}\cdot$$

$$\left\{\left[\frac{-\chi}{\xi} - e^{-\alpha D + \frac{D}{L_p}}\right] e^{-\frac{2D}{L_p}} e^{\frac{x}{L_p}} + \frac{\chi}{\xi} e^{-\frac{x}{L_p}} + e^{-\alpha x}\right\} \tag{7}$$

with

$$\chi = \left(S_b + \frac{D_p}{L_p}\right) e^{\frac{H-D}{L_p}} e^{-\alpha D} - \left(S_b - \alpha D\right) e^{-\alpha H},$$

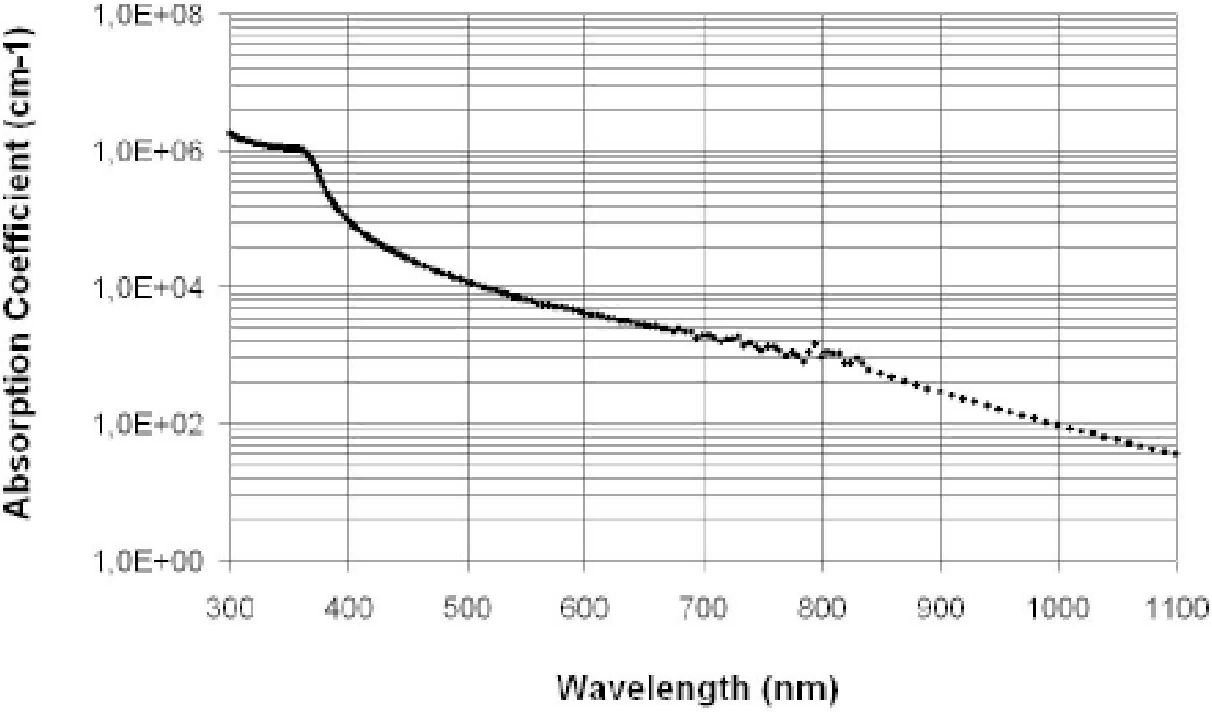

Fig. 6. Absorption coefficient of silicon photodiode as a function of wavelength.

$$\xi = -\left(S_b + \frac{D_p}{L_p}\right)e^{\frac{H-D}{L_p}} - \left(S_p - \alpha D\right)e^{-\frac{H}{L_p}},\ \ L_p = \left(D_p \tau_p\right)^{1/2}.$$

Using $p_n = p_n(x) \rightarrow I_p = -qAD_p dp/dx$ relation the generated current due to minority carriers in the n side of photodiode can be obtained.

$$I_p = \frac{qF_0 A\alpha L_p}{\left(\alpha^2 L_p^2 - 1\right)}\left\{\frac{\left[S_b - \alpha D_p\right]e^{-\alpha H}\left[e^{\frac{H-2D}{L_p}} + e^{-\frac{H}{L_p}}\right] - 2S_b e^{-\frac{\left(1+\alpha L_p\right)D}{L_p}}}{-\left(S_b + \frac{D_p}{L_p}\right)e^{\frac{H-D}{L_p}} - \left(S_b - \alpha D_p\right)e^{-\alpha H}} + \alpha L_p e^{-\alpha H}\right\}. \tag{8}$$

The current generated within the depletion region was also calculated by considering Eq. (3a) and Eq.(5a), with no recombination of electron-hole pairs as

$$I_d = \text{const.} + \frac{\left[1 - e^{-\alpha D}\right]}{\alpha}. \tag{9}$$

The total current generated within photodiode is the sum of currents in Eqs. (8) and (9). The internal QE of photodiode is the generated current divided by photon flux absorbed by the photodiode.

In Eqs. (8) and (9), α is the absorption coefficient, S_b is the back surface recombination velocity, L_p is the diffusion length of holes, D and H are the thicknesses depletion region and n side of photodiode respectively. To solve these equations, the absorption coefficient of silicon photodiode needs to be calculated. The remaining parameters can be obtained by fitting the calculated quantum efficiency measurements to the measured ones.

The optical absorption coefficient is related to the imaginary part of index of refraction k by $\alpha(\omega) = 4\pi k/\lambda$ [18]. It is obvious that to calculate absorption coefficient the imaginary part of index of refraction k is

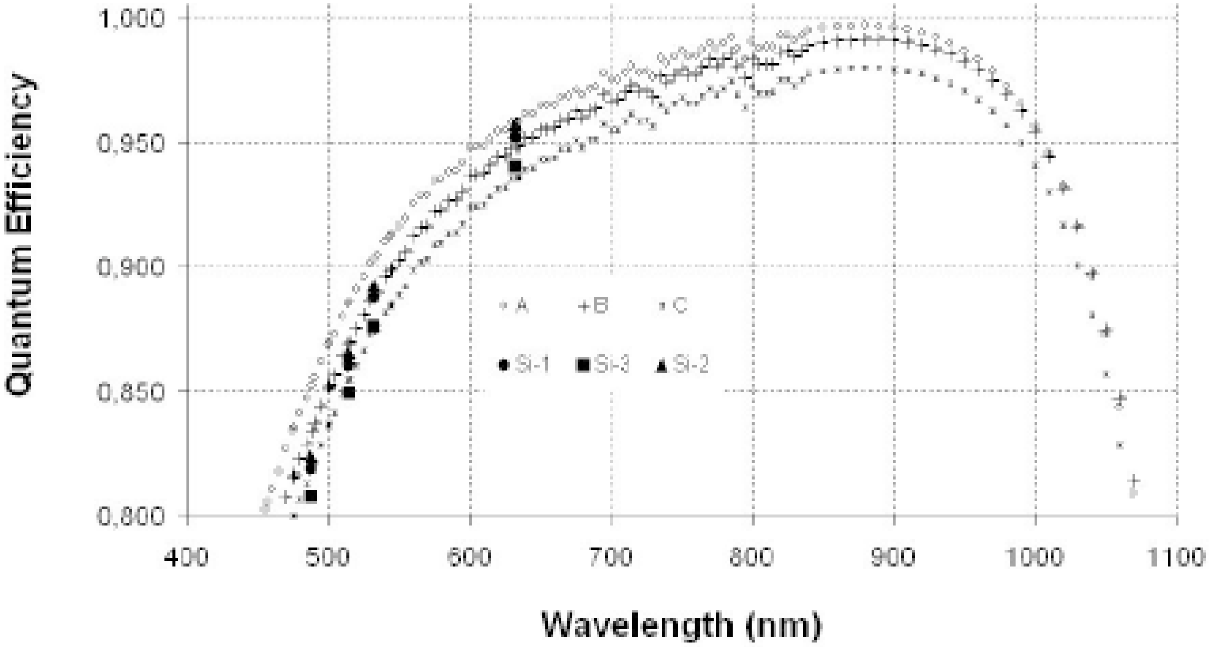

Fig. 7. Internal quantum efficiency of silicon photodiode at different beam diameters.

needed. For the photodiode used in this work this parameter was obtained after determining the optical phase angle using reflectance measurements at normal incidence of light and Kramers–Kronig relations [18]. Using Fresnell's equations, the index of refraction k as functions of experimentally measured reflectance $R(\omega)$ and phase angle $\theta(\omega)$ between incident and reflected flux can be expressed as [19]

$$k = \frac{2\sqrt{R}\sin\theta}{1 + R - 2\sqrt{R}\cos\theta}. \tag{10}$$

By using Kramers–Krönig dispersion relations between the real and imaginary parts of complex function $\ln r = \ln|r| + i\theta$, the phase angle $\theta(\omega)$ is given by [20]

$$\theta(\omega_0) = \frac{1}{2\pi}\int_0^\infty \ln\left|\frac{\omega - \omega_0}{\omega + \omega_0}\right| \frac{d}{d\omega}\left[\ln R(\omega)\right] d\omega. \tag{11}$$

This equation indicated that after having measured experimentally $R(\omega)$ it is possible to calculate $\theta(\omega)$. The methods used for the reflectance measurements and the calculations of phase angle are described in [21]. Using the calculated phase angle values obtained from Eq. (11) the imaginary part of refraction index k and therefore absorption coefficient, as a function of wavelengths was determined as shown in Fig. 6.

With the substitution of absorption constants we get the internal QE. The QE values were then corrected by using reflectance looses as given in Eq. (2) and they were fitted to the measured values by adjusting diffusion coefficient, diffusion length, thickness of photodiode, and back surface recombination velocity. The modeled QE values as a function of wavelength at different beam diameters for both silicon and silicon based trap detectors are shown in the Figs. 7 and 8. Reflectance values of silicon based trap detectors were taken from our previous work [11].

The responsivity of photodiodes, which allows one to determine how much detector signal will be available for a specific application, are defined by the diode surface reflectance and the QE is expressed as [22]

$$R = \left[1 - \rho(\lambda)\right] IQE(\lambda)\frac{en\lambda}{hc}, \tag{12}$$

where e is the elementary charge, λ is the wavelength in vacuum, h is the Planck constant, c is the speed of light in vacuum, n is the refractive index of medium, $\rho(\lambda)$ is the reflectance of trap detector and $IQE(\lambda)$ is the internal QE of detector.

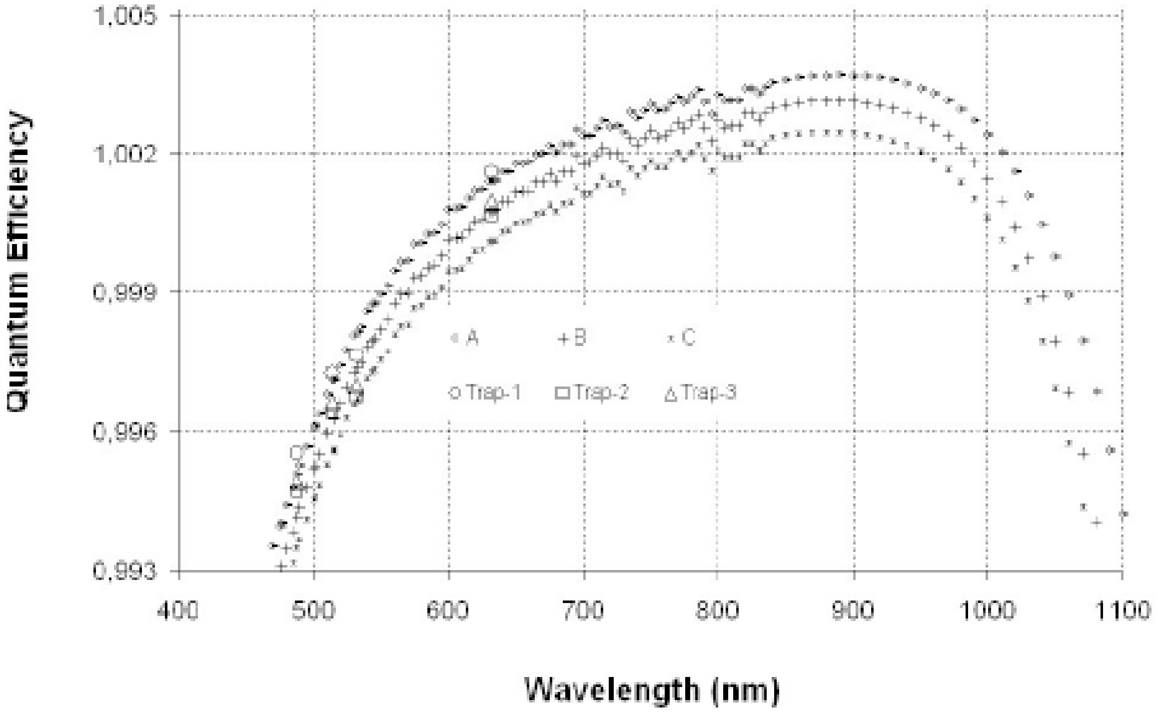

Fig. 8. Internal quantum efficiency of silicon based trap detectors at different beam diameters.

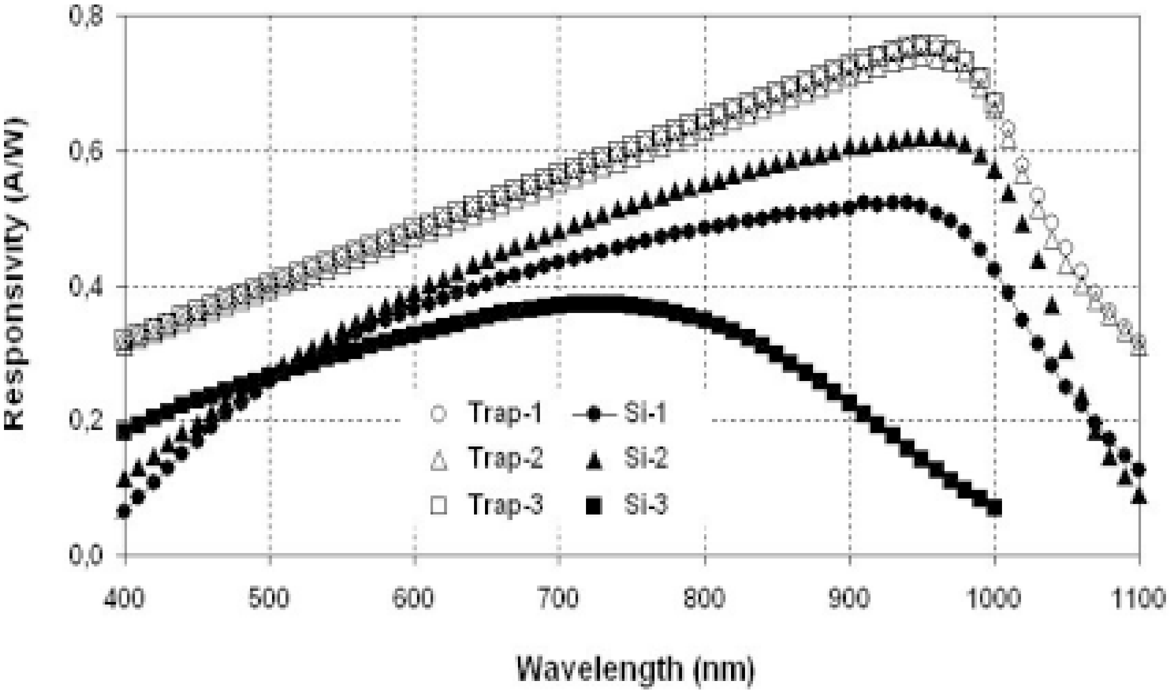

Fig. 9. Responsivity of silicon and silicon based trap detectors.

The units of responsitivity are either amperes/watt (alternatively milliamperes/milliwatt or microamperes/microwatt, which are numerically the same) or volts/watt, depending on whether the output is an electric current or a voltage. In the Fig. 9 responsivities of photodiodes and trap detectors are displayed.

5. CONCLUSION

In this work both measurement of quantum efficiency of silicon photodiode at the laser wavelengths and the theoretical approach that are used for modelling of quantum efficiency were described. In the measurement part; responsivity, reflectance, surface homogeneity, effects of beam diameter were discussed at the power stabilized (~10^{-5}) laser wavelengths. In the theoretical part, variation of internal quantum efficiency of silicon photodiode having a very thin p layer (p<<n) was studied by considering negligible amount of recombinations in the p and depletion regions. The internal quantum efficiency as a function of absorption coefficient and some optical constants of photodiode was modelled by making some assumptions for the variation of minority charge carriers in the neutral n region of photodiode. Then by fitting the calculated internal quantum efficiency values to measured ones and by correcting them with the reflectance we obtained the external QE values.

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