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Spatial Non-uniformity Measurements of Large Area Silicon Photodiodes

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Abstract

Accurate determination of the responsivity of silicon photodiodes are highly desired in photometry. The change of responsivity over the surface, the so-called spatial non-uniformity, effects power measurements especially in photodiodes with large active areas. To study this effect, first an intensity-stabilized laser source-optics has been established. A purpose-built step-motor controlled two axis micro mechanical stage has been designed to scan the photodiode surface. In this study, the technique and the results of the uniformity mapping of large area research-grade silicon photodiodes which were measured on the purpose-built set-up are presented.

Key Words: Photometry, Silicon Photodiode, Spatial Uniformity

1. Introduction

Photometry is the field in optics which deals with measurements in the visible range between 380 and 780 nm, based on the visual response of the human eye. Silicon photodiodes are reasonable light sensors and thus commonly employed in photometry [1-4].

The determination of the spectral responsivity characteristics of the silicon photodiode is the most important factor for photodetectors [5-7]. In a standard spectral responsivity measurement, the detector is under-filled, i.e. the incoming light is adjusted so that all the light is falls inside the active area of the photodiode. An ideal photodiode should have a spatially uniform responsivity which has same value over the active area regardless of the position of the incoming beam [8]. In the case of uniform responsivity, for the radiation sensed by a photodiode at different locations of its sensitive surface, the same electrical output signal is generated. But due to various effects, such as crystal structure of silicon, fabrication quality, radiation, heat conduction and convection losses, the photometers suffer from spatial non-uniformities [9]. Mostly inhomogeneities of the photodiode material itself causes non-uniformity, resulting in inhomogeneity in bulk recombination centres at longer wavelengths [10] and in surface recombination centres at shorter wavelengths [11-12]. Therefore, for the same optical beam with the same radiant power coming to different parts of a photodetector, generally, different output signals are generated [13]. This effect causes to have different signal readings and extra uncertainties that must be evaluated for a successful calibration of these devices [14].

There are important steps to be considered in a uniformity measurement set-up; such as the construction of a controlled XY stage, intensity stabilization of the laser beam, dimensional and optical properties of incident light, the temperature effects and the linearity in the responsivity of the silicon photodiode. To minimize and overcome the effect of nonlinearity the silicon photodiodes, laser signals less than 0.1 mW were used, an intensity range where the responsivity is intensity independent in the type of photodiodes used [15].

Temperature was monitored during the measurements the temperature did not vary more than 0.2°C. Three p-n type photodiodetypes manufactured by Hamamatsu were selected for study; namely, S1337-11, S1337-1010BQ and S1227-1010BQ [16]. The active areas were 10 x 10 mm^2 for all type of the photodiodes. The S1337-1010BQ and S1227-1010BQ both have quartz windows but the S1337-11 is windowless.

2. Optical Setup

For the spatial uniformity measurements, a stable Gaussian beam with uniform circular power distribution is required. Overall experimental setup used for measuring the spatial uniformity of a photodiode is depicted in Figure 1. Here, the measurement system can be divided into two parts: i) stabilized beam preparation optics and ii) the XY photodiode positioning system.

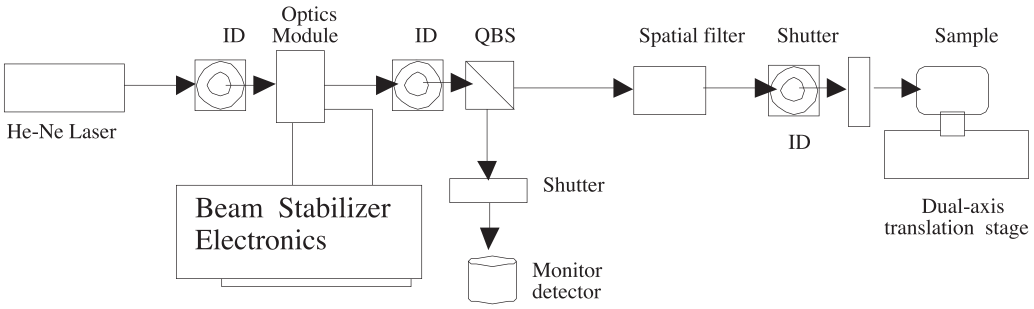

Figure 1. Measurement setup for spatial non-uniformity measurements.

A computer controlled dual-axis translation stage was constructed on which to mount and position the photodiodes. The resolution of the motion-control system was investigated using a calibrated micrometer which is carefully connected along the position axis, to the one end of translational positioning stages. The vertical movement uncertainty was found as $\pm$ 2 μm and the horizontal uncertainty was $\pm$ 4 μm. For all 1 cm^2 photodiodes, the scanned area was 12 mm x 12 mm with 0.5 mm steps in both directions. After each scan in the horizontal direction, the photodiode moved one step in the vertical direction and then another horizontal direction scan was started. The scans were continued in the reverse direction and average readings were recorded. The scans were started at the upper left corner and finished at the lower right corner of the photodiode.

The spatial uniformity was measured by moving the photodiode at equal steps in both directions perpendicular to beam direction. Before every scan, the surface of the photodiodes were aligned perpendicular to the optical axis at the four corners and the centre of the photodiode by using the reflected beam.

A He-Ne laser at 633 nm was used as the radiation source. Optical power of the laser beam was stabilized by means of a commercial laser power controller system which has a electro-optic modulator fed by the measured output signal. Alternatively, the stabilized signal was observed during the measurements by means of an auxiliary monitor detector. A calibrated S2281 silicon photodetector was used for this purpose. A quartz beam splitter cube (QBS) was added to the beam direction to reflect a portion of the laser beam on to the monitor-detector.

A spatial filter which consists of a 10X objective and a 25 μm pinhole was used to generate a beam with a clean profile. Just after the spatial filter, a plano convex lens (not shown in the figure) was placed in line with the bean to align a slightly convergent laser beam with a small beam spot at the detector surface. During all measurements, the gaussian beam spot diameter on the detector surface was about 1.0 mm. The beam size was checked using 1 mm diameter aperture, which was calibrated with a profile projector system.

Three iris diaphragms (ID) were used to reduce the effect of interreflections in the laser beam, ie. the effect of stray lights. Two shutters were used in the system for dark-current background measurements. Measurements were normally carried out under the dark environmental conditions. The photodiodes were also placed in a closed box with the interior painted matt black in order to reduce the influence of stray light.

The photodiode and the monitor photodetector output signals were amplified with calibrated transimpedance amplifiers which were connected to digital voltmeters (DVM). The stability of the light was characterized by the ratio of photodiode and monitor detector signals.

The measurements were made under special environmental conditions since photodiodes are quite sensitive to environmental temperature changes. The temperature was air-conditioned at 23.0 ± 0.2°C and temperature changes were recorded during the measurement with a Pt 100 temperature sensor, which was mounted in the dark box.

3. Laser Intensity Stabilization

Due to the nature of the power measurement, any power instability an the order of 10^{-4} may result in an incorrect reading. It is, therefore, quite difficult to make such sensitive measurements by using a normal monochromator or laser light output. Development of a laser based light stabilization optics optimized for a certain wavelength is a prerequisite for a uniformity measurements facility. For this purpose, a second quartz beam splitter was put just nearby the laser source to split the laser beam. Another monitor photodetector was employed to read the power level before power stabilization.

In order to check the level of stabilization, the two monitor photodiode signals were compared. Output stability of the laser was seen to be around $5 \mathrm{x} 10^{-3}$ without stabilization. It was also found that, after a 35–40 minute period, the laser signal can be made stable within an order of $4 \mathrm{x} 10^{-5}$ with the stabilization optics. Both signals are given in normalized form in Figure 2 for comparison of amplitude fluctuations.

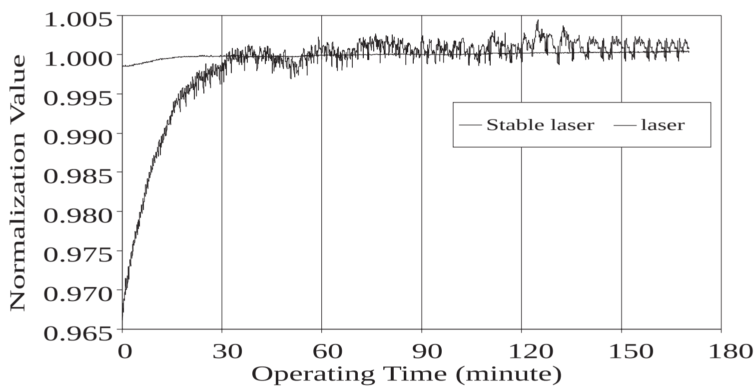

Figure 2. Comparison of Intensity Stabilization Levels.

4. Measurement Results

The spatial uniformity of three different types single silicon photodiodes (S1337-11, S1337-1010BQ and S1227-1010BQ) were measured in our system at 633 nm laser wavelength. The diameter of the laser beam at the photodiode surface was adjusted as 1.0 mm for the measurements. Figures 3a-c shows the three dimensional plots of non-uniformity measurements for three types of silicon photodiodes:

Surface contour plots with respect to the average responsivity at the active area are also given, respectively, in Figure 4.

It is a common practice to state that a research-grade silicon photodiode is suitable as a transfer standard if the nonuniformity is less than 0.5 % over the active area, or less than 0.25 % within the 50 % center of the active area [8]. The relative standard deviations of two sets of measurements (to obtain the mean relative responsivity values within the 50 % central area) of S1337-11, S1337-1010BQ and S1227-1010BQ photodiodes are $4 \mathrm{x} 10^{-4}$, $9 \mathrm{x} 10^{-4}$ and $8 \mathrm{x} 10^{-4}$ respectively. Responsivity of the S1337-11 windowless type single photodiode have better flatness in uniformity compared to other 1010BQ type single photodiodes. In general, the responsivities of the measured photodiodes over the 80% interior were constant to better than 0.15%. Moreover, it was seen that the responsivity of all photodiodes increased towards the edges possibly due to the thicker SiO_2 layer and therefore higher light absorption in those regions.

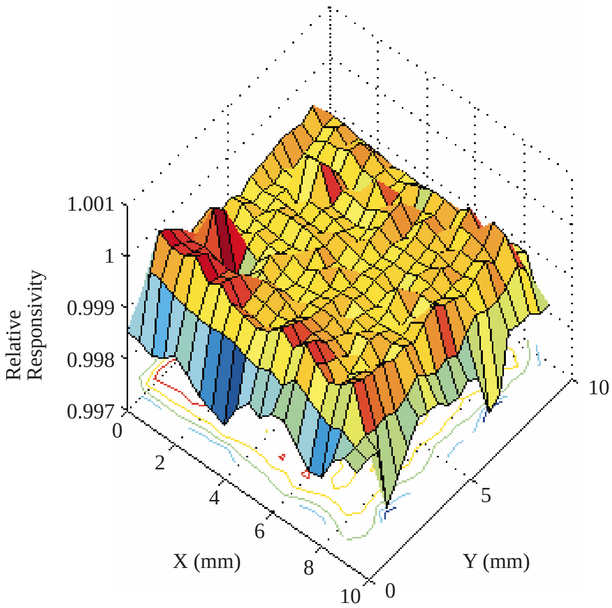

Figure 3a. Spatial relative responsivity of S-1337-11 type photodiode.

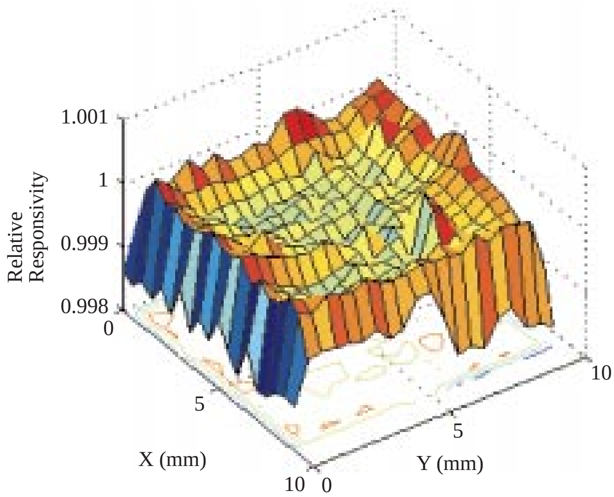

Figure 3b. Spatial relative responsivity of S-1337-1010BQ type photodiode.

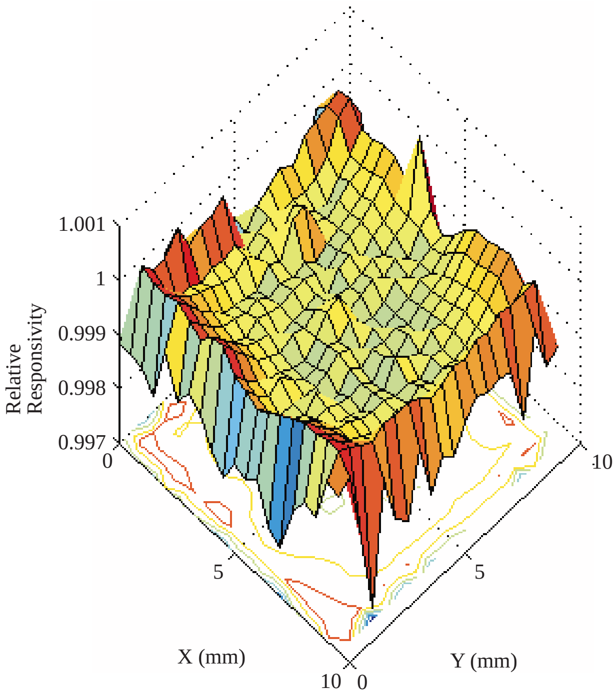

Figure 3c. Spatial relative responsivity of 1227-1010BQ type photodiode.

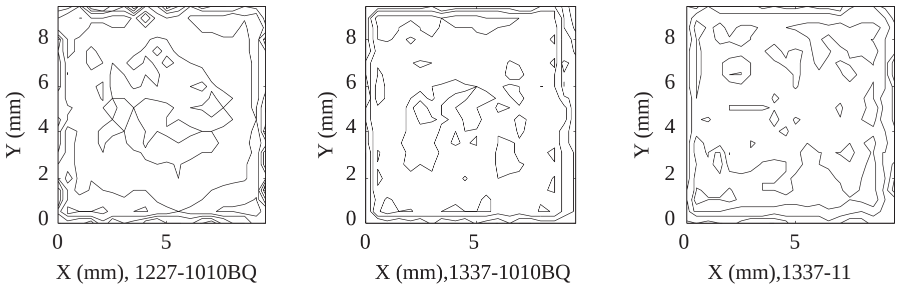

Figure 4. Spatial Uniformity Contour Mapping of the same Si Photodiodes

5. Conclusions

An intensity-stabilized He-Ne laser-based set-up had been established to investigate the responsivity behaviour of silicon photodiodes with 10x10 mm area. In the responsivity measurements, a stable Gaussian beam and uniform circular power distribution was used. For this purpose, the laser intensity stabilization has been achieved in the order of 10^{-5} at 633 nm and the power level used. Photodiodes with most uniform responsivity surfaces has been identified to be used as reference standards and in building photometers. For high accuracy transfer standards, Hamamatsu 1337-11, 1337-1010BQ and 1227-1010BQ photodiodes are among the most ideal. Using the results from the measurements in this paper as a guideline, we have decided to use 1337-11 photodiodes for our trap detectors, 1337-1010BQ photodiodes as transfer standard photodetectors, and 1227-1010BQ for the Photometer Heads.

No direct formulation was determined as a relation between the local responsivity and the distance from the detector centre due to the non-uniform changing of responsivity over the photodiode surface.

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