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Characterization of GaAsP trap detector for radiometric measurements in ultraviolet wavelength region

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A trap detector was constructed of three Schottky-type $10 \times 10 \text{ mm}^2$ GaAsP photodiodes. The spectral reflectance of the trap detector was calculated from the measured spectral reflectances of a single GaAsP photodiode in the wavelength range between 240 and 600 nm, and compared to the measured spectral reflectance of the trap detector at three laser wavelengths. The absolute spectral responsivity of the trap detector was measured. The internal quantum efficiencies (IQE) of the trap detector and a single photodiode were calculated in the wavelength region between 250 and 400 nm from the spectral reflectances and responsivities. The comparison revealed reduction of the apparent IQE of the trap detector as compared to the single photodiode at the level of 10%. The spatial uniformity of the responsivity of the trap detector was measured, and the corresponding uncertainty component at 325 nm was calculated to be 4×10^{-4} . The effect of moderate ultraviolet exposure at the level of 50 mJ/cm^2 on the stability of the responsivity of GaAsP photodiode was studied and found to be below 2×10^{-3} at all used wavelengths.

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I. INTRODUCTION

High accuracy radiometric measurements in the ultraviolet (UV) wavelength range set some specific requirements for semiconductor photodiodes. These requirements include solar blindness, long-term stability of spectral properties, and stability of spectral responsivity under UV exposure. In addition, the photodiode with suitable properties has to be commercially available with large area, typically at least $5 \times 5 \text{ mm}^2$, and with good spatial uniformity. Furthermore, slowly varying spectral responsivity and reflectance of the photodiode would be preferable as these parameters are typically interpolated between the measured values. The actual choice of the photodiode is typically a trade-off between these properties.

Gallium arsenide phosphide (GaAsP) Schottky-type photodiodes, which have cut-off wavelength around 610 nm, are widely used as working standard detectors in the UV wavelength region. The photodiodes are coated with a thin gold layer, which acts both as the Schottky contact and as a protection against oxidation. The photodiodes meet to some extent most of the requirements listed earlier. In addition, the photodiodes are commercially available with the effective area up to $10 \times 10 \text{ mm}^2$.

Several research groups have investigated the properties of GaAsP photodiodes.^{1–8} In addition to favorable properties of the photodiodes, the research has also revealed some problems. The responsivity of GaAsP photodiodes is typically 2–3 times lower as compared to silicon photodiodes. The spectral responsivity changes rapidly under intense UV exposure.⁶ In addition, the spatial uniformity of the responsivity of the studied GaAsP photodiodes has been modest.^{5,6}

The trap detector configuration^{9,10} has been used with great success with silicon photodiodes for more than two

decades. The detectors have some excellent properties. Typically the trap detectors are polarization insensitive, have low reflectance, and their spatial uniformity is better as compared to the individual photodiodes. The trap detector configuration has also been used with other semiconductor materials, like PtSi, InGaAs, and Ge.^{11–13} However, not all the photodiodes enable to take the full advantage of the trap detector configuration. For example, high absorption of the incident light in the protective layer of the photodiode may reduce the efficiency of the trap detector, where two out of three photodiodes are at 45° angles with respect to the incident light and thus the absorption increases. As a result, the responsivity of the trap does not exceed the responsivities of the single photodiodes significantly.^{12,13}

In this study, we have investigated the use of GaAsP Schottky-type photodiodes in the trap detector configuration. To the best of our knowledge, this is the first published report on the properties of an assembled GaAsP trap detector. We show that the increase of absorption in the coating layer of the photodiodes in the trap detector configuration is modest and thus the photodiodes are suitable to be used in the trap detector configuration. We have studied the spectral properties of GaAsP trap detector and its spatial uniformity. The wavelength range of our special interest was from 250 to 370 nm as the spectral responsivity of silicon detectors is difficult to interpolate in this spectral range. We have tested the stability of the responsivity of GaAsP photodiode under moderate UV exposure, corresponding to the levels used during the calibration and in typical applications. Furthermore, we discuss the advantages related to the smooth spectral shape of the responsivity of GaAsP trap detector in the wavelength range between 250 and 370 nm, which seems

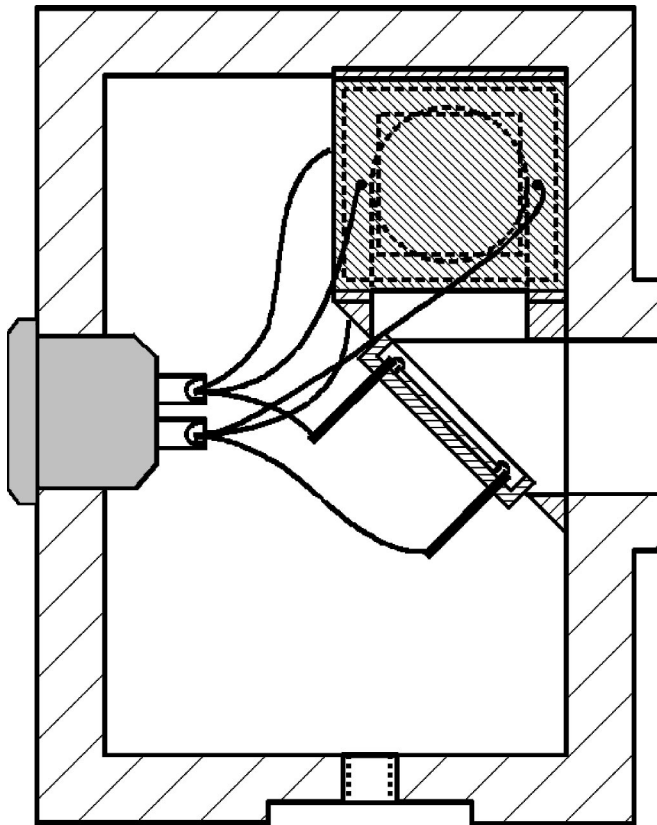


FIG. 1. Schematic drawing of GaAsP trap detector. The third diode is located behind the body part keeping the diodes together.

to enable interpolation of the spectral responsivity with higher accuracy as compared to a silicon detector in this range.

II. GaAsP TRAP DETECTOR

The working principle of the three-element reflection trap detector, originally used with the silicon photodiodes, is presented in Ref. 10. The photodiodes inside the trap detector are aligned in such a way, that the incident light is reflected five times on three photodiodes. Four reflections are at 45° angle of incidence with the normals of the diodes and one is at 0° . This configuration makes the trap detector practically polarization independent, as the polarization of the light is switched between the *s*- and *p*-polarizations due to the orientation of the photodiodes.

Our trap detector (Fig. 1) has been constructed of three G2119 photodiodes, commercially available from Hamamatsu. The photodiodes are made of GaAsP bulk material covered with a thin gold layer acting as a Schottky contact. The diodes are rectangular with $10 \times 10 \text{ mm}^2$ effective area. Protective glass windows, originally installed on top of each photodiode, have been removed. All photodiodes are connected electrically in parallel. The shunt resistance of G2119 photodiode is specified by the manufacturer to be around $0.7 \text{ G}\Omega$, measured at 10 mV voltage. Accordingly, the calculated shunt resistance for the trap detector is $0.23 \text{ G}\Omega$.

The design of the trap detector allows it to be comfortably used for a large variety of radiometric applications. For

example, it can be easily combined with our filter radiometers,¹⁴ where presently silicon trap detectors are used.

The effective area of the trap detector, 36 mm^2 , is smaller than the area of a single photodiode, as the diodes are tilted. However, this value is enough for most of the radiometric applications. For example, the limiting aperture of our filter radiometers is around 7 mm^2 . The angle of view of the trap detector is calculated based on the geometry of the trap to be around 6° . This value is also high enough for most of the applications.

As compared to silicon photodiodes, the responsivity of G2119 GaAsP photodiodes in the UV is somewhat more sensitive to the variations of the ambient temperature. The temperature coefficient, specified by the manufacturer for the wavelength range between 250 and 400 nm , is 1×10^{-3} per $^\circ\text{C}$. In the laboratory environment, the ambient temperature is typically stable at least within 1°C . Thus the uncertainty contribution arising from the instability of the temperature of the detector is 1×10^{-3} . This could be further reduced by integrating some temperature stabilization elements into the trap detector. However, even at the level of relative uncertainty of 1×10^{-3} , this component can be considered fairly low as compared to the combined standard uncertainty of optical power responsivity scale of HUT, which is between 1% and 2.5% in this spectral range, and also to the typical uncertainty levels of other National Metrology Institutes.¹⁵

III. CHARACTERIZATION

A. Spectral reflectance

There are several practical reasons why the spectral reflectance of a trap detector should be known. First, it enables the calculation of the internal quantum efficiency from the measured spectral responsivity. Next, if the trap detector is used with reflective optics in front of it, for example, in a filter radiometer, the interreflections between the optics and the trap detector have to be taken into account.

The reflectance of a trap detector, ρ_{trap} , can be calculated from the known reflectances of the single photodiodes used in the trap detector. The calculation takes into account the configuration of the trap detector and the reflectances of the photodiodes at angles of 0° and 45° for both polarization planes, $\rho(0^\circ)$, $\rho_s(45^\circ)$, and $\rho_p(45^\circ)$, respectively. The reflectance can be calculated as

$$\rho_{\text{trap}} = \rho(0^\circ) \cdot \rho_s^2(45^\circ) \cdot \rho_p^2(45^\circ). \quad (1)$$

We used our high accuracy gonioreflectometer¹⁶ to measure the spectral reflectance of a GaAsP photodiode in the wavelength range between 240 nm and 600 nm [Fig. 2(a)]. The measurements were conducted at the angles of incidence of 45° , 30° , and 10° with the light polarized linearly sequentially in *s*- and *p*-planes. The measurement beam with a 5.4-nm bandwidth was produced by a double monochromator-based light source system. The reflectance at the normal incidence was calculated by extrapolation of the measured reflectances. The reflectance of GaAsP trap detector was calculated from the data using Eq. (1) [Fig. 2(b)].

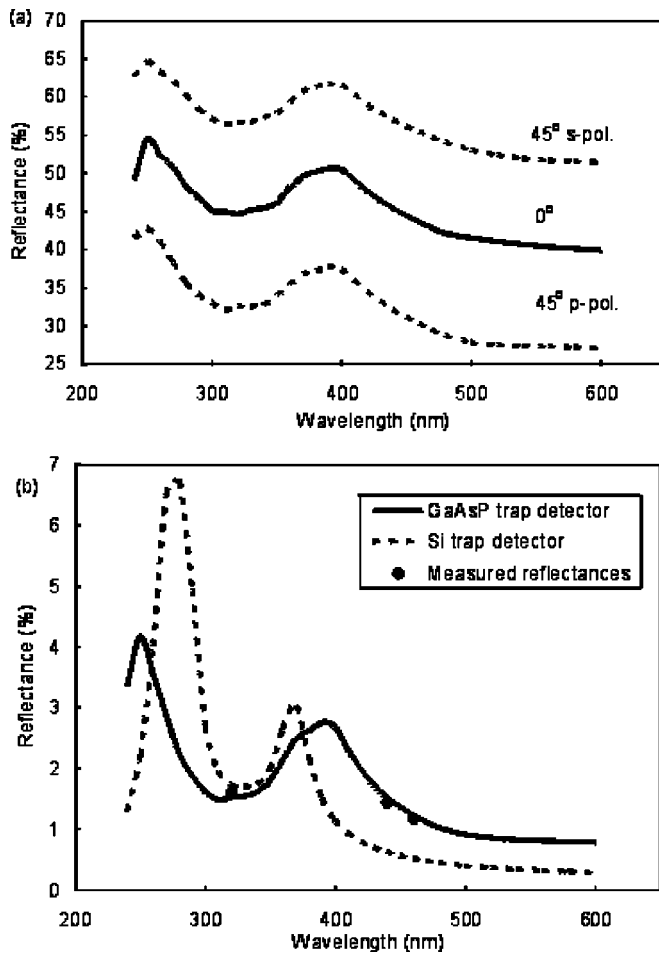


FIG. 2. (a) Spectral reflectances of a single GaAsP photodiode at two angles of incidence in different polarization planes. (b) Calculated spectral reflectance of GaAsP trap detector compared to typical spectral reflectance of a silicon trap detector. The circles indicate measured reflectances for the assembled GaAsP trap detector.

We also measured the reflectance of the trap detector as a whole at several laser wavelengths in order to verify the calculated reflectance. The measurements were conducted at 325 nm, 442 nm, and 457 nm. During the measurements, the trap detector was tilted 0.5° from the direction of the incident light in order to be able to measure the power of the reflected light. The relative deviations of the calculated reflectances of the trap detector from the measured values were around 5×10^{-2} at all wavelengths. This corresponds approximately to the uncertainty of the measurements.

B. Spectral responsivity and IQE

The absolute spectral responsivity of the trap detector [Figs. 3(a) and 3(b)] was measured with a monochromator-based spectrophotometer¹⁷ using a silicon trap detector as a reference. The reference detector had been calibrated with the cryogenic radiometer at three argon ion laser wavelengths. In addition, it had been calibrated with a spectrally flat detector. The responsivity of the trap detector at all measured wavelengths is approximately 2 times higher as compared to the responsivity of a single photodiode under normal incidence. This is the result of the reduced reflectance of the trap detector. The internal quantum efficiencies (IQE) of

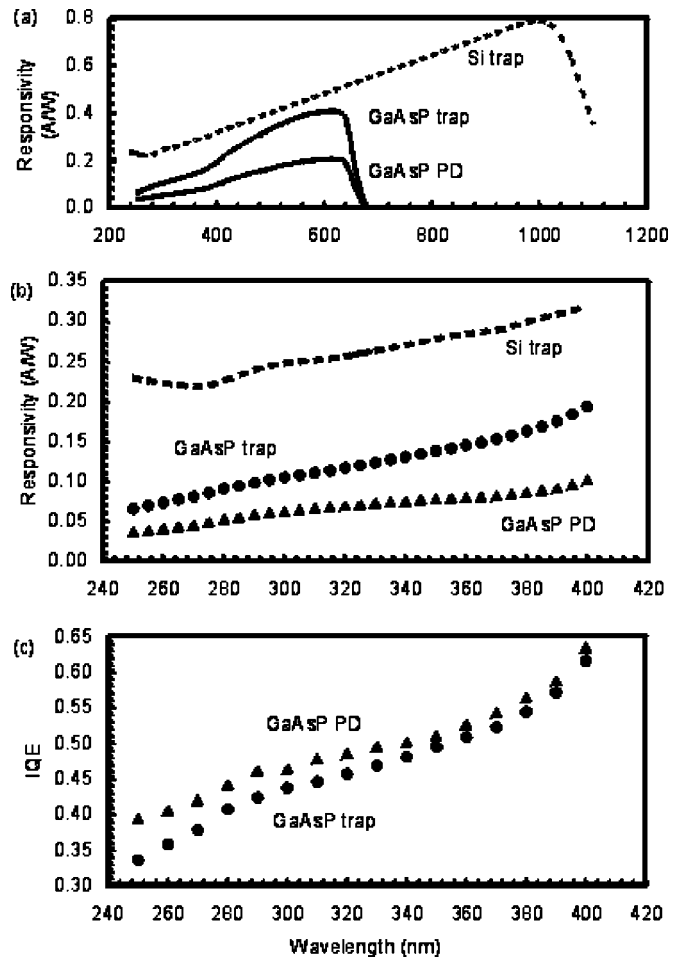


FIG. 3. (a) and (b) Spectral responsivity of GaAsP trap detector (GaAsP trap) as compared to spectral responsivities of a silicon trap detector (Si trap) and of a single GaAsP photodiode under normal incidence (GaAsP PD). (c) Internal quantum efficiencies of GaAsP trap detector and of a single GaAsP photodiode under normal incidence.

GaAsP trap detector and of a single GaAsP photodiode under normal incidence were calculated from the measured spectral responsivities and reflectances [Fig. 3(c)]. The comparison reveals a modest reduction of the IQE for the trap detector. This systematic difference varies between 3% at 400 nm and 14% at 250 nm. The probable reason for this effect is the increased absorption in the Schottky contact layer of the photodiodes in the trap detector configuration, where two of the photodiodes are at 45° with respect to the incident light and thus the path length of the light through the contact layer is longer.

The decrease of the IQE of a single GaAsP photodiode with the increase of the angle of incidence of light was also measured at two laser wavelengths, 325 and 442 nm. We compared the IQE at two angles of incidence, 10° and 45° , for both *s*- and *p*-polarized light. The decrease of the IQE at 45° , calculated as an average of the measurements with *s*- and *p*-polarized light, was found to be 3.7% and 3.1% at the wavelengths of 325 and 442 nm, respectively. The results are in agreement with the apparent decrease of the IQE in trap detector, discussed in the previous paragraph.

The spectral responsivity of GaAsP trap detector is a smooth function of wavelength in the range between 250 nm

and 370 nm. On the contrary, the spectral responsivity of a typical silicon detector has a complicated structure at 275 nm, which makes its responsivity difficult to interpolate in this wavelength range [Fig. 3(b)]. The physical explanation is that while silicon has the peaks of its dielectric functions, corresponding to the direct electron transitions in the energy-band structure, at around 275 nm and 370 nm, the corresponding peaks for the used GaAsP compound appear around 250 nm and 390 nm. The slowly varying region between the peaks is wider for GaAsP and coincides comfortably with the wavelength region of our interest. Furthermore, as the wavelength of the lowest direct transition of GaAsP, 250 nm, is around 25 nm lower as compared to the silicon, the effect of the multiple electron-hole pair generation by a single photon, which is quite complicated to predict,¹⁸ should be less significant above 250 nm. Reduced reflectance of the trap detector also contributes to the spectral smoothness as the peaks, appearing in the spectral reflectance at the same wavelengths, are around one decade lower (Fig. 2).

In practice, the spectral density of the calibration points, and thus the required number of the calibrations at different wavelengths, depends on the accuracy of the interpolation between the measured values. Accordingly the smoothness of the responsivity reduces the effort needed, especially if the calibration is performed with a cryogenic radiometer.

C. Spatial uniformity of the responsivity

The spatial uniformity of the optical power responsivity was measured first separately for the single photodiodes. The measurements were carried out at two helium-cadmium laser wavelengths, 325 nm and 442 nm. The $1/e^2$ diameter of the laser beam was approximately 2 mm. We tested four photodiodes and rejected one, which had a 4% responsivity peak near to its center. Typically, the responsivity was lowest in the center and increased close to the edges of the photodiodes by approximately 5%.

Next the trap detector was assembled, and the measurements were repeated with the trap detector. The measurements were conducted at the same laser wavelengths with similar diameters of the laser beam. The measured responsivities at 325 nm, relative to the responsivity at the center of the trap detector, are shown in Fig. 4. At an average, the spatial uniformity of the assembled trap detector was approximately 2 times better as compared to that of the single photodiodes.

The accuracy of the alignment of the trap detector with the incident light beam is in the order of 0.5 mm for most of the measurement applications. From the measured spatial uniformities of the GaAsP trap detector at 325 nm and 442 nm wavelengths, the corresponding uncertainty contribution to the responsivity of the trap detector was calculated. In case of a beam with 3 mm diameter, the relative standard uncertainty contribution is 4×10^{-4} for both of the wavelengths.

Due to the systematic increase of the responsivity towards the edges of the detector, it is necessary to apply a small correction to the responsivity of the trap detector if the beam sizes in the calibration and in the application are not

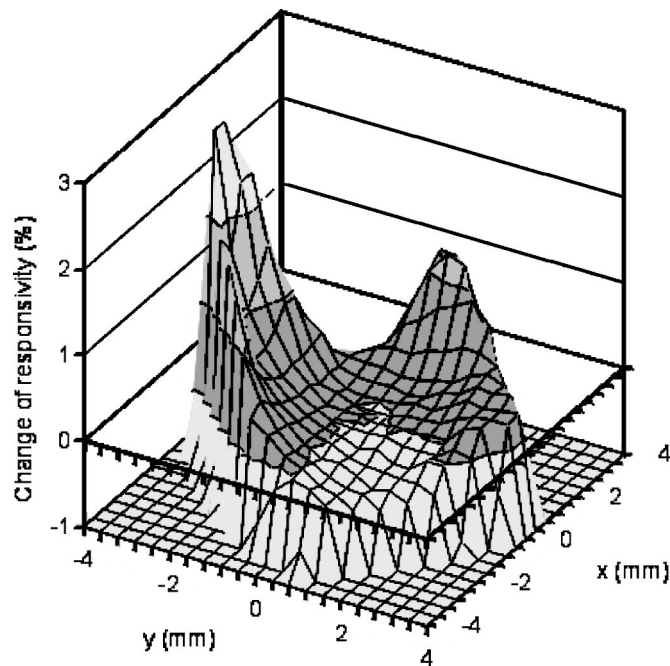


FIG. 4. Spatial uniformity of GaAsP trap detector at 325 nm, measured using a 2 mm beam.

equal. For example, the relative difference between the average responsivities of the trap detector for a 2-mm beam and for a 3-mm beam is 2×10^{-4} .

D. Stability under UV exposure

It has been shown that the responsivity of semiconductor detectors, especially of the silicon detectors, changes rapidly under the intense UV exposure.⁵ The change depends on the wavelength, intensity, and exposure of the radiation. The responsivity remains unstable also some time after the UV exposure. The effects are somewhat random and complicated to predict. It has also been demonstrated, that the change of the responsivity of GaAsP Schottky photodiodes is slower as compared to the corresponding change in the responsivity of a silicon photodiode.⁴

In order to use our GaAsP trap detector as a stable radiometric standard detector, we had to test that the responsivity of the used photodiodes does not change under the moderate UV irradiance and limited exposures, which are used in the case of our typical applications. For that purpose we repeated the spectral responsivity measurements of a photodiode in the spectrophotometer over the wavelength range of 250–400 nm several times. The measurements were conducted with 5 nm bandwidth and 25 nm step. The time of irradiation was approximately 1 min at each used wavelength. The diameter of the spectrophotometer beam was 3 mm. During the measurements, the radiant exposures at each wavelength varied between 6 mJ/cm² and 73 mJ/cm². We could not detect any systematic change in the spectral responsivity during the measurements. In the case of the spectral irradiance measurements with our standard FEL lamps at 0.5 m distance, the exposures and irradiance levels are of the same order of magnitude. Thus the uncertainty

contribution arising from the damage of the incident UV radiation is below the repeatability of our test measurements, 2×10^{-3} .

IV. DISCUSSION

We have constructed a GaAsP trap detector which is suitable to be used as a working standard detector for the optical power measurements in ultraviolet wavelength range. The reduction of the internal quantum efficiency of the trap detector as compared to a single photodiode at normal incidence was measured to be at the level of 10%. This effect arises probably from the increased absorption in the Schottky contact layer, made of gold, on the top of the photodiodes. However, as the reflectance of the trap detector is approximately 10 times lower than the reflectance of a single photodiode, the spectral responsivity of GaAsP trap detector is still approximately 2 times higher as compared to a single GaAsP photodiode.

The spectral power responsivity of GaAsP trap detector is a smooth function of wavelength between 250 nm and 370 nm. This is advantageous in the respect of the interpolation of spectral properties between the measured values.

We have shown that despite the rapid change of the responsivity under intense UV exposure, indicated by the other research groups, GaAsP photodiodes do not change their properties under the modest UV exposures at the level of

50 mJ/cm^2 , used in our calibrations and in the spectral irradiance measurements in filter radiometer configuration. However, only longer experience will reveal possible slower changes in the responsivity.

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