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Characterization of germanium photodiodes and trap detector

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Abstract

We have developed and characterized new detectors based on germanium (Ge) photodiodes to be used in the wavelength region between 900 and 1650 nm. The effects of spatial uniformity, temperature and low shunt resistance on the spectral responsivity measurements are studied. Our results for the spatial uniformities show improvements as compared with earlier studies. The spectral reflectances of a Ge photodiode and trap detector are also studied, and the trap reflectance is found to be less than 10^{-4} at wavelengths longer than 900 nm. The results of this study show that with careful use, the large area Ge photodiodes can offer a cost-effective alternative as compared with InGaAs photodiodes of similar diameters.

Keywords: photodetectors, germanium, infrared, radiometry, metrology

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Ge technology dates back to 1950s when it was extensively studied for transistors. This research made good quality crystals available for studies of the photoelectric and optical properties. Nowadays large area Ge photodiodes are commercially available at moderate prices, in contrast to InGaAs photodiodes of similar diameters. Therefore, Ge photodiodes potentially offer a cost-effective technique for accurate radiometric measurements in the near-infrared wavelength region.

The first trap configuration consisting of four silicon photodiodes was introduced by Zalewski and Duda in 1983 [1]. The idea behind their trap detector was to reduce the amount of back-reflected light and thus to increase the external quantum efficiency. Eight years later Fox modified the original trap configuration to be less polarization sensitive by arranging three photodiodes to lie in a three-dimensional configuration [2]. To this day, a large range of different photodiodes have been used to construct trap detectors for the ultraviolet [3], visible [1, 2] and infrared [4, 5] wavelength regions. The trap detectors have low reflectance, and they are polarization insensitive. However, not all photodiodes are able to take full advantage of the trap configuration for reasons such as protective layer absorption [3] or the effects of low shunt resistance. The use of Ge photodiodes in the trap configuration was reported earlier by Stock *et al* in 2003 [4]. Unfortunately, the spatial nonuniformities of Ge photodiodes have traditionally been at the level of ∼1% [6, 7], making InGaAs technology more attractive for high accuracy radiometric measurements in the near-infrared wavelength region.

Our present detector-based scale of spectral irradiance covers the wavelength range between 290 and 900 nm [8]. In order to meet the needs of our customers, we are in the process of extending our measurement capabilities to the near-infrared region. We have started this work by characterizing Ge photodiodes and a trap detector consisting of three Ge photodiodes. Studied quantities are spectral responsivity and spectral reflectance. The effects of spatial uniformity, temperature and low shunt resistance on the responsivity measurements are studied as well. We also analyse the anti-reflection (AR) coating of the photodiodes based on the spectral reflectance measurements at oblique angles of incidence.

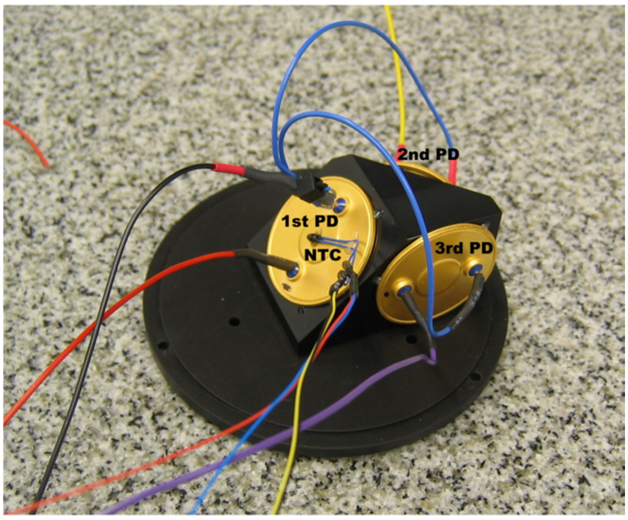

Figure 1. The body part of the trap detector, where the photodiodes (PD) and the NTC temperature sensor are marked. Light enters the trap from the direction of the table.

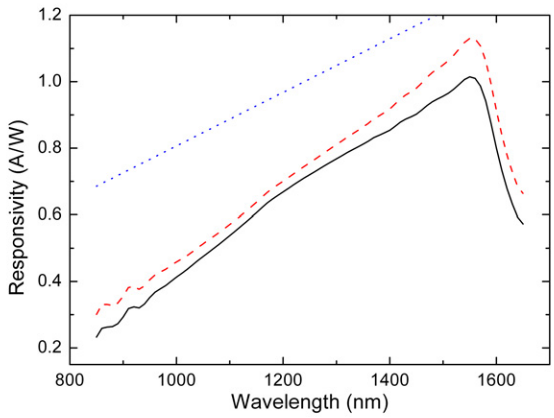

Figure 2. Spectral responsivities of a Ge photodiode (solid black line) and the Ge trap detector (dashed red line) at the temperature of 22.4 °C. The spectral responsivity for an ideal detector with unity quantum efficiency is also shown (dotted blue line).

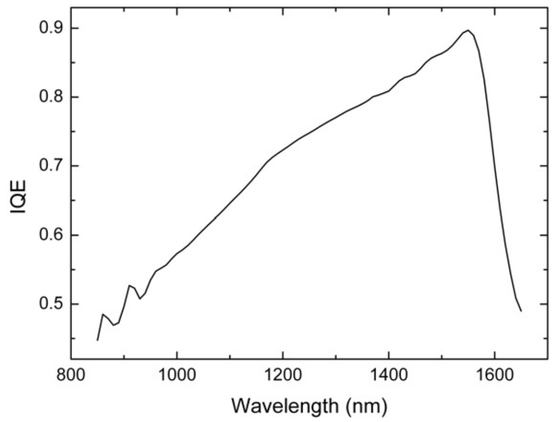

Figure 3. Internal quantum efficiency of a Ge photodiode.

The most severe drawback of the Ge photodiodes is their low shunt resistance and in turn significant dark current, which are both temperature dependent [9]. However, these problems can be reduced to a satisfactory level by either monitoring the detector temperature or constructing temperature stabilization. In addition, our results show that the spatial uniformity of the Ge photodiodes has improved significantly over the years and is now at the level of ~0.1% at the wavelengths of 1308 and 1550 nm. The reflectance of the Ge trap detector is found to be below the level of 10^{-4} in the near-infrared wavelength region. This makes the Ge trap detector applicable for filter radiometry, such as spectral irradiance measurements, which are affected by inter-reflections between the detector and filter.

2. Construction of germanium detectors

All the studied photodiodes are commercially available from Judson Technologies LLC, and their model number is J16-P1-R10M-SC. These photodiodes are large area diodes with a circular active area of 10 mm. The photodiodes were ordered without protecting windows.

After individual photodiodes were characterized, we constructed a trap detector consisting of three photodiodes, of which the first two are aligned at 45° angles with respect to the incoming light and the third one is at normal incidence. Five inter-reflections take place inside the trap before the reflected light leaves the detector [2]. The body part of our trap detector, which keeps the photodiodes together, is presented in figure 1.

3. Characterization of germanium detectors

3.1. Spectral responsivity and IQE

The spectral responsivity measurements were carried out by using the monochromator-based reference spectrometer built at the Helsinki University of Technology (TKK) [10]. The spectral responsivity results for a Ge photodiode and the Ge trap detector are illustrated in figure 2. In the responsivity measurements, the spectral bandwidth was 2.9 nm. The spectral temperature coefficient of the Ge detectors was also studied and found to vary from −0.003 to 0.007 °C^{-1} in the wavelength range of 850 to 1650 nm. The spectral dependence of the temperature coefficient is similar to that found in earlier studies [4]. The temperature of the detectors was monitored during the responsivity measurements.

The internal quantum efficiency (IQE) of Ge photodiodes was calculated from the measured spectral responsivity and reflectance. The results presented in figure 3 show that there are significant internal losses with the studied photodiodes. The absorption coefficient and the penetration depths with Ge photodiodes are strongly dependent on the wavelength. The long wavelength photons can penetrate deeper into the photodiode than short wavelength photons, and therefore they are mainly absorbed in different volume elements of the detector [11]. Since Ge has no native oxide that is suitable as a durable resistant passivation and anti-reflection coating, the concentration of recombination centres is much higher close to the interface between the Ge wafer and the passivation layer than at Si–SiO_2 interfaces in the case of silicon detectors. Therefore, the decrease of IQE at short wavelengths is due to the recombination at the interface Ge–passivation layer and within the front region of the diode [12].

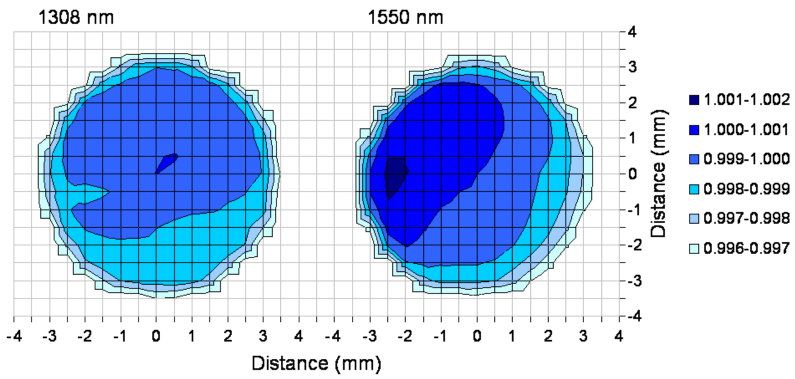

Figure 4. Spatial uniformities of a Ge photodiode (PD 3 in table 1) at 1308 and 1550 nm wavelengths. The legend lists relative differences compared to the central value of the photodiode.

Table 1. Uncertainty in responsivity arising from spatial nonuniformity. The values are based on the assumption that the beam size of 3 mm could be misaligned by 1 mm to any direction from the centre point of the photodiode (PD). For the trap detector, the effect of 0.5 mm misalignment is also demonstrated.

		Detector					
		PD 1	PD 2	PD 3	PD 4	Trap 0.5 mm	Trap 1 mm
900 nm	Maximum difference (%)	1.77	1.48	0.79	1.38	n.m.[a]	n.m.[a]
	Standard deviation (%)	0.55	0.45	0.22	0.41	n.m.[a]	n.m.[a]
1308 nm	Maximum difference (%)	0.16	0.04	0.06	0.21	0.08	0.23
	Standard deviation (%)	0.05	0.01	0.02	0.07	0.03	0.06
1550 nm	Maximum difference (%)	0.35	0.20	0.13	0.17	0.07	0.32
	Standard deviation (%)	0.11	0.06	0.04	0.05	0.02	0.08

[a] Not measured.

These internal losses can possibly have an effect on the long-term stability of the Ge photodiodes. Large area Ge photodiodes having even worse IQE have been studied, and their ageing rate between 1100 and 1800 nm was found to be lower than ±0.5% per year [12]. Even though these results cannot be used to predict other diodes, they give an estimate for the severity of the ageing effect. Another important issue to be considered is radiation damage, which is not expected to take place in the wavelength region above 900 nm, where Ge photodiodes are normally used with moderate power levels of ∼20 mW at the maximum. Earlier studies have shown that even the reversible fatigue effects with Ge photodiodes are negligible if the diodes are radiated at wavelengths longer than 600 nm at power levels of a few microwatts [13].

3.2. Spatial uniformity

The spatial uniformity was measured at 900, 1308 and 1550 nm wavelengths with three different laser sources. The measurement set-up features a cube beam splitter to divide the beam into a monitor detector and the Ge detector under study. Figure 4 presents the spatial uniformities for a single Ge photodiode at 1308 and 1550 nm wavelengths. In these measurements, the beam diameter was 1 mm and the step size was 0.5 mm. The results show that the Ge photodiodes can attain a spatial uniformity level which is comparable to that reached with silicon photodiodes in the wavelength region where they have significant responsivity [7]. This is a beneficial property, when Ge photodiodes are considered to be used, for instance, as transfer standards in fibre optic power measurements [14].

With 3 mm beam diameter scanned over a circular central region of 5 mm in diameter, the spatial nonuniformity of all four Ge photodiodes is within 0.1% at 1308 and 1550 nm wavelengths. At 900 nm, the spatial nonuniformity varies between 0.22 and 0.55% for the four studied diodes. Table 1 shows the uncertainties arising from the spatial nonuniformity with four Ge photodiodes and the Ge trap detector, if the possible alignment error is taken as 1 mm. Typically the trap configuration improves spatial uniformity, but in the present case the opposite effect seems to occur: in the trap configuration the light illuminates a larger area on the first two photodiodes, because they are aligned at 45° angle with respect to the incident light. As the spatial uniformity of a single diode is worse closer to the edges and single photodiodes have reasonably low reflectances, the trap configuration does not improve the spatial uniformity.

3.3. Spectral reflectance

The reflectances of the photodiodes were measured using the absolute gonioreflectometer programmed for specular reflectance measurements [15]. Additional comparison measurements were done with three different lasers at 1308, 1523 and between 1480 and 1600 nm wavelengths. The results for a Ge photodiode are shown in figure 5.

The reflectance of the Ge trap detector was calculated based on the results of reflectance measurements of the

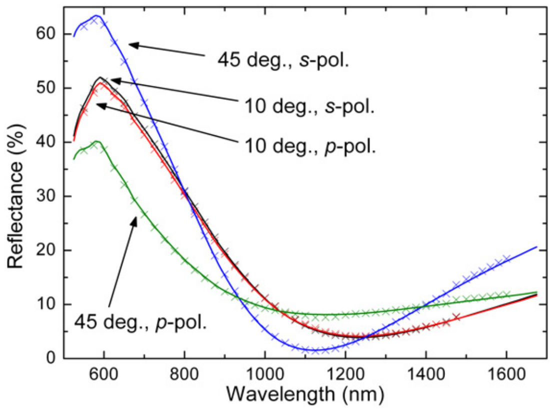

Figure 5. Spectral reflectance of a Ge photodiode measured at 10 and 45° angles of incidence with both s- and p-polarizations. The crosses indicate the measurement data and the continuous lines present modelled reflectance values.

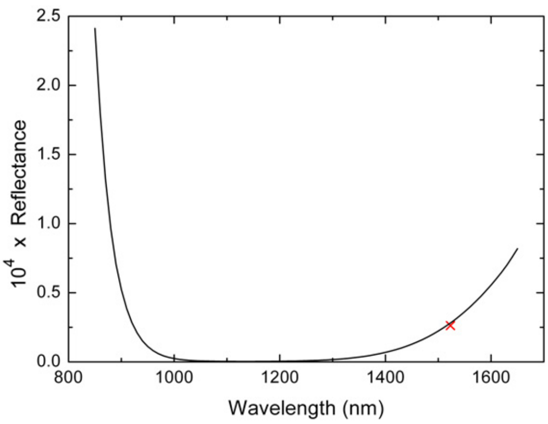

Figure 6. Calculated spectral reflectance of the Ge trap detector (solid black line) verified with a laser measurement at 1523 nm wavelength (red cross).

individual Ge photodiodes. The trap reflectance is needed, for instance, to make the inter-reflection correction when the components of filter radiometers are characterized separately. The calculated result was verified with a laser measurement at 1523 nm. The spectral reflectance of the Ge trap detector is plotted in figure 6.

All the Ge diodes have AR coating, which explains the shape of the spectral reflectance curves. In the analysis of AR coating, we combine the spectral reflectance measurements at oblique angles of incidence with a mathematical model that considers a thin homogeneous layer of a dielectric material deposited on a macroscopically thick plane-parallel substrate [16]. For the substrate characteristics, we use tabulated values for bare Ge [17].

The analysis reveals that the thicknesses of the AR coatings of the four Ge photodiodes vary between 175 and 182 nm. As the refractive index is found to be at the level of ∼1.7, the optical thickness of the anti-reflection coating is approximately 300 nm, which makes it optimized for the wavelength region around 1200 nm. The refractive index of the thin layer on top of the photodiodes is obtained from the model, and the data are plotted in figure 7. The analysis does not reveal any reasonable absorption in the AR coating.

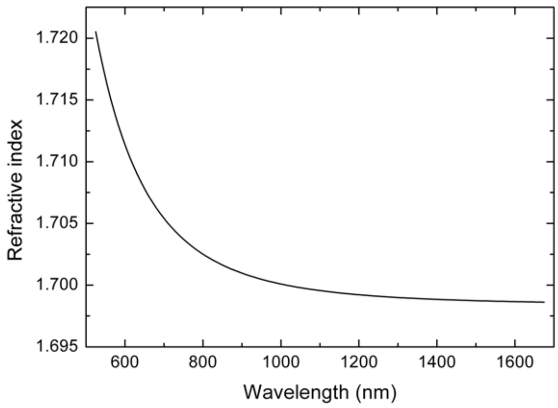

Figure 7. Refractive index obtained for the AR coating of the Ge photodiodes.

Table 2. Effect of the shunt resistance R_s of the Ge photodiodes and Ge trap detector when combined with the dc input impedance of the current-to-voltage converter (CVC).

Sensitivity of CVC (A V^{-1})	DC input impedance of CVC (Ω)	Effect on apparent responsivity as compared with the zero dc input impedance of the CVC (%)	
		Photodiode ($R_s \sim 5$ kΩ)	Trap ($R_s \sim 1.7$ kΩ)
10^{-3}	1	−0.02	−0.06
10^{-4}	1	−0.02	−0.06
10^{-5}	100	−1.96	−5.66
10^{-6}	100	−1.96	−5.66
10^{-7}	10^4	−66.7	−85.7
10^{-8}	10^4	−66.7	−85.7

3.4. Effects of shunt resistance on responsivity

The current signals of the diodes are measured using current-to-voltage converters (CVC). When the gain setting of the CVC is adjusted, the input impedance of the device can change. Therefore, the relatively low shunt resistances of the Ge photodiodes (∼5 kΩ) and trap detector (∼1.7 kΩ) need to be taken into account. Otherwise, a significant ratio of the photocurrent can flow through the shunt resistance instead of the CVC. If the input impedance of the CVC increases from 1 to 100 Ω, this can affect the apparent responsivity of the Ge photodiodes or of the trap detector by ∼2 or ∼6%, respectively. The estimated effects for Stanford Research Systems SR570 CVC [18] have been demonstrated in table 2. The temperature dependence of the shunt resistance also affects the apparent responsivity values in table 2. This temperature coefficient is of the order of 0.003% $°C^{-1}$ for the 1 Ω input impedance. As the input impedance increases to 100 Ω, the temperature coefficient becomes two orders of magnitude higher with a value of 0.3% $°C^{-1}$.

Due to the low shunt resistance of the Ge detectors, the detector and the amplifier should be constructed and characterized as a packet. One commonly used technique to increase the shunt resistance of the photodiode is the use of a bootstrap transimpedance amplifier [19]. Otherwise, Ge photodiodes demand extra care, if used as transfer standards, as they should be calibrated for the different gain settings or the shunt and input impedances should be measured in order to be able to apply corrections. Even though the photodiodes have low shunt resistance, their noise level does not become a critical issue as the Johnson and dark current noise do not exceed the level of a few picoamperes.

4. Conclusions

The large area Ge photodiodes provide a cost-effective alternative for InGaAs photodiodes of similar sizes in accurate measurements of near-infrared radiation. These photodiodes nowadays have good spatial uniformities, and the Ge trap detector offers a favourable alternative for the applications where we want to avoid harmful inter-reflections. These properties make Ge detectors a reasonable choice for, e.g., fibre optic power measurements and applications of spectral irradiance measurements using filter radiometers. However, accounting for the effects of shunt resistance, dark current and temperature sensitivity of the Ge detectors requires a high degree of understanding and awareness from the user which limits their use as transfer standard detectors.

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