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Temperature dependency of responsivity and dark current of nearly ideal black silicon photodiodes

Juha Heinonen[a], Antti Haarahiltunen[a], Michael Serue[a], Daria Kriukova[a], Ville Vähänissi[b], Toni P. Pasanen[b], Hele Savin[b] and Mikko A. Juntunen[a]

[a]ElFys, Inc., Tekniikantie 12, 02150 Espoo, Finland; [b]Department of Electronics and Nanoengineering, Aalto University, Tietotie 3, 02150 Espoo, Finland;

ABSTRACT

A high-quality photodiode has high signal-to-noise ratio (SNR), which is ultimately defined by the responsivity and dark current of the photodiode. Black silicon induced junction photodiodes have been shown to have nearly ideal responsivity across a wide range of wavelengths between 175-1100 nm at room temperature (RT). Here we present their spectral responsivity stability and dark current at different temperatures. Both quantities show temperature dependencies similar to conventional pn-junction photodiodes, proving that black silicon photodiodes maintain their improved SNR also at temperatures other than RT.

Keywords: Black silicon, dark current, responsivity, silicon, photodiode, signal to noise ratio

1. INTRODUCTION

A high-quality photodiode has high signal-to-noise ratio (SNR), which is ultimately defined by the responsivity and dark current of the photodiode [1]. The dark current has a strong temperature dependency which is why the most common way of improving SNR is to cool down the photodiode below room temperature (RT). This way the dark current can be reduced to a negligible level compared to the noise of the readout electronics while maintaining responsivity on similar level than at RT. However, in many applications cooling is not an option and the photodiode needs to be operated in temperatures at or above RT due to restrictions set by e.g. design or cost. Therefore, it is essential to know the temperature dependency of the responsivity and dark current in order to ensure high enough SNR at the operation conditions.

Black silicon (b-Si) induced junction photodiodes have been shown to have nearly ideal responsivity across a wide range of wavelengths between 175-1100 nm at RT [2]. Here we have studied their spectral responsivity stability at temperatures between RT and 340 K. We also present dark current measured between 220 K and 290 K which is compared to temperature dependency of conventional pn-junction photodiodes.

2. EXPERIMENTAL

The photodiodes used in dark current measurements were fabricated in the project the project "Application of black silicon surface treatment to photodiodes and silicon drift detectors" supported by the European Space Agency (ESA), using process similar to the one previously described in [3], [4]. The dark currents measured from black silicon induced junction photodiodes were compared to conventional pn-junction photodiodes manufactured on the same wafer [4]. The temperature dependency of external quantum efficiency (EQE) of black silicon photodiodes was measured from ElFys standard photodiode having an active area of 25 mm^2.

EQE spectra were measured with a setup where the photodiode was illuminated with Bentham ILD-D2-QH-24 dual-lamp light source. The lamp was coupled to Bentham TMC300_0060 monochromator where the wavelength was selected with 10 nm bandwidth and focused on the photodiode. The EQE values were calibrated against the Newport 818-UV photodetector. The current was measured using Keithley 237 source measure unit and system was controlled via LabVIEW program. The stage where the photodiode was mounted can be heated by resistive heating element which allowed the EQE measurements at temperatures higher than RT. The temperature of metallic heating plate was monitored using Pt-100 resistor by placing the sensor close to the chip which was under measurement. Heater metal was also used as contact to chip back surface and the top contact to the chip was made by a needle.

The dark current was measured at temperatures between 220 K and 290 K in steps of 10 K. The cooling was provided by liquid nitrogen and the temperature was controlled using a heating resistor. The dark current was measured using HP4155A parameter analyzer. Both anode and guard ring were set at zero bias and cathode voltage was swept in the measurements.

3. THEORETICAL ANALYSIS OF TEMPERATURE DEPENDENCY OF RESPONSIVITY

In order to theoretically analyze temperature dependency of EQE, we used the PC-1D simulator version 5.9 [5] to calculate the internal quantum efficiency (IQE) of the photodetectors as described in Refs. [4], [6]. The front surface reflection R_f is assumed to be zero in the analysis. The default Auger recombination and radiative recombination parameters of the simulation tool and initially long (several ms) Shockley-Read-Hall bulk recombination lifetime have been used. A relatively low 10 cm/s effective back surface recombination velocity S_{eff} was used together with the mirroring effect of the back surface to get a reasonable fitting of EQE results from different temperatures. The aluminum oxide (Al_2O_3) passivation layer and induced junction was modeled with negative surface charge of -3×10^{12} cm^{-2} and with surface recombination velocity of 1×10^5 cm/s for electrons and holes. The light absorption coefficient and it's temperature dependency was calculated following power law and tabulated data from Ref. [7]. The analysis was done for wavelengths longer than 400 nm as PC-1D simulator does not contain model for secondary ionization, which occurs at UV-wavelengths.

4. RESULTS AND DISCUSSION

4.1 Temperature dependency of spectral responsivity of black silicon photodiodes

The EQE of black silicon photodiodes at different temperatures across the full spectral range of 200-1100 nm is shown in Figure 1a (zoomed-in view in Figure 1b) together with simulation results. The change in responsivity is greatest in near infrared (NIR) part of the spectrum, which is expected based on temperature dependency of silicon absorption coefficient [7]. PC-1D model captures rather well the temperature dependency in NIR wavelength range as shown in Figure 1b, but it is unable to simulate real EQE in the ultraviolet range (Figure 1a). The measured relative change of responsivity with temperature together with simulated one is shown in Figure 2a (zoomed-in view in Figure 2b). Results in Figure 2 show that observed behavior agrees with the theoretical temperature dependency of photodiode internal quantum efficiency qualitatively at visible and quantitatively at NIR. The results indicate that the relative change of responsivity with temperature can almost entirely be explained by temperature dependency of absorption coefficient in this case.

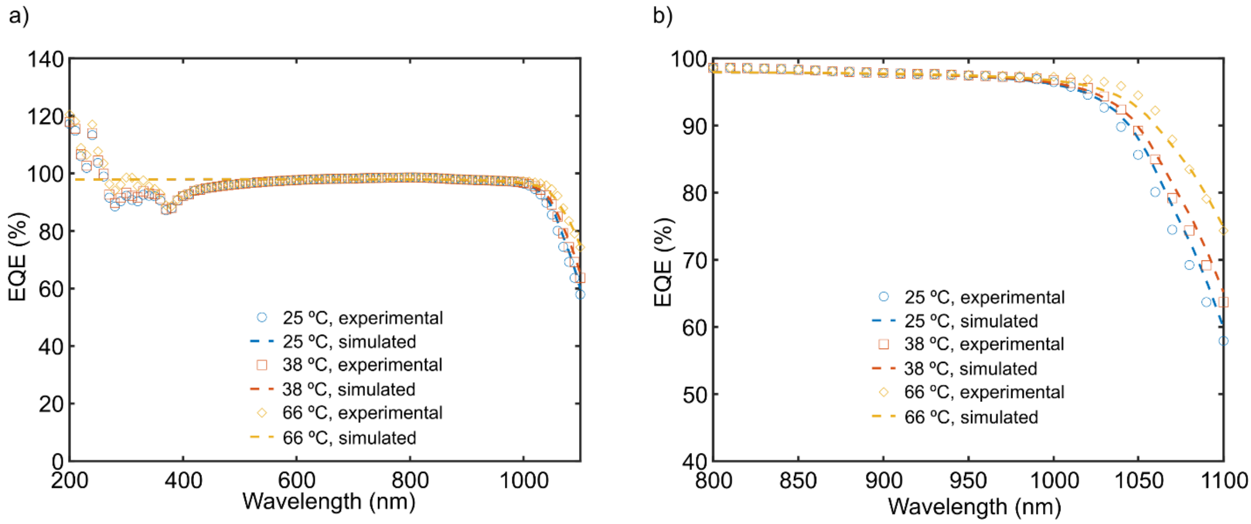

Figure 1. The measured spectral response of black silicon photodiodes at different temperatures (symbols) and corresponding simulations (solid line) a) full range 200-1100 nm and b) zoomed-in view of the NIR part.

The relative change of responsivity with temperature in Figure 2a is less than 1×10^{-3} up to 1000 nm. Temperature dependency is about half of the silicon trap detector [8] at 1000 nm. At visible wavelengths, the temperature dependency decreases below 0.1×10^{-3} (Figure 2b). These results suggest that induced junction black silicon photodiodes alone could be used as replacement of silicon trap detectors, but this still requires confirmation of the results with a setup having lower uncertainty. The deviation in responsivity results indicates that upper limit for temperature dependency is $\pm0.3\times10^{-4}$/K in range of 500-900 nm, which is similar or smaller than reported for Hamamatsu S1337 photodiode [9].

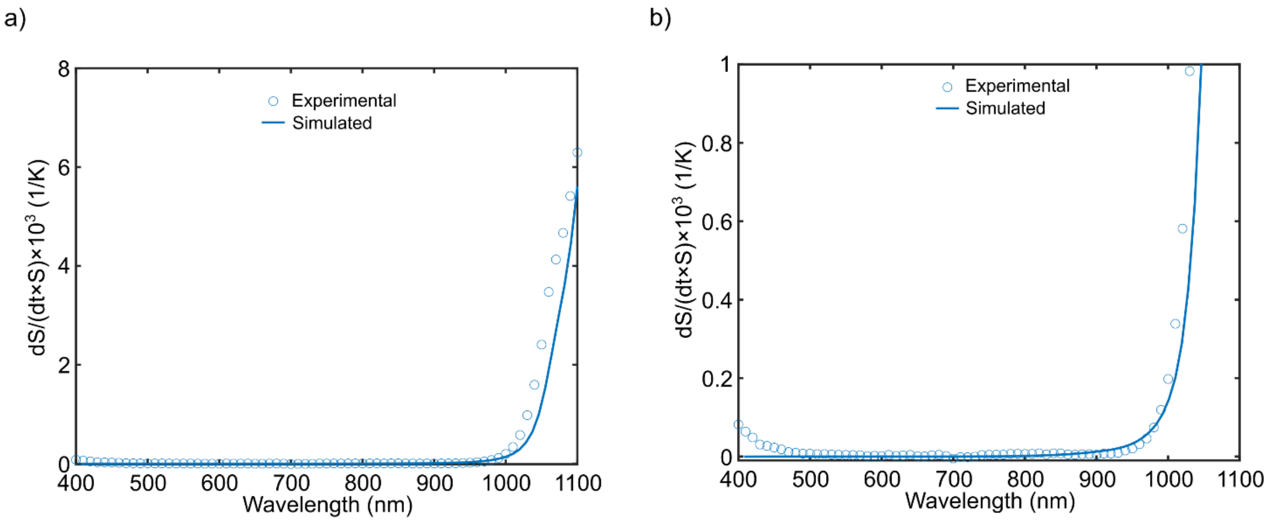

Figure 2. The relative change of responsivity of black silicon photodiodes with temperature a) full range and b) zoomed-in view of less than 1×10^{-3}/K. The symbols indicate experimental results and solid line simulation results.

In ultraviolet range signal level is a few to tens of nanoamperes, which makes signal hard to differentiate from dark current at higher temperatures, where the dark current increases. The signal minimum occurs in the range of 300-400 nm, which explains inconsistent results in Figure 1 a) in this wavelength range. However, it seems that temperature dependency of responsivity starts to increase again at UV as shown in Figure 3 where 220 nm measurement results are shown as an example. At 220 nm the relative change of responsivity with temperature is around 0.9×10^{-3}/K. This is in the same range than the temperature dependency reported in Ref [10].

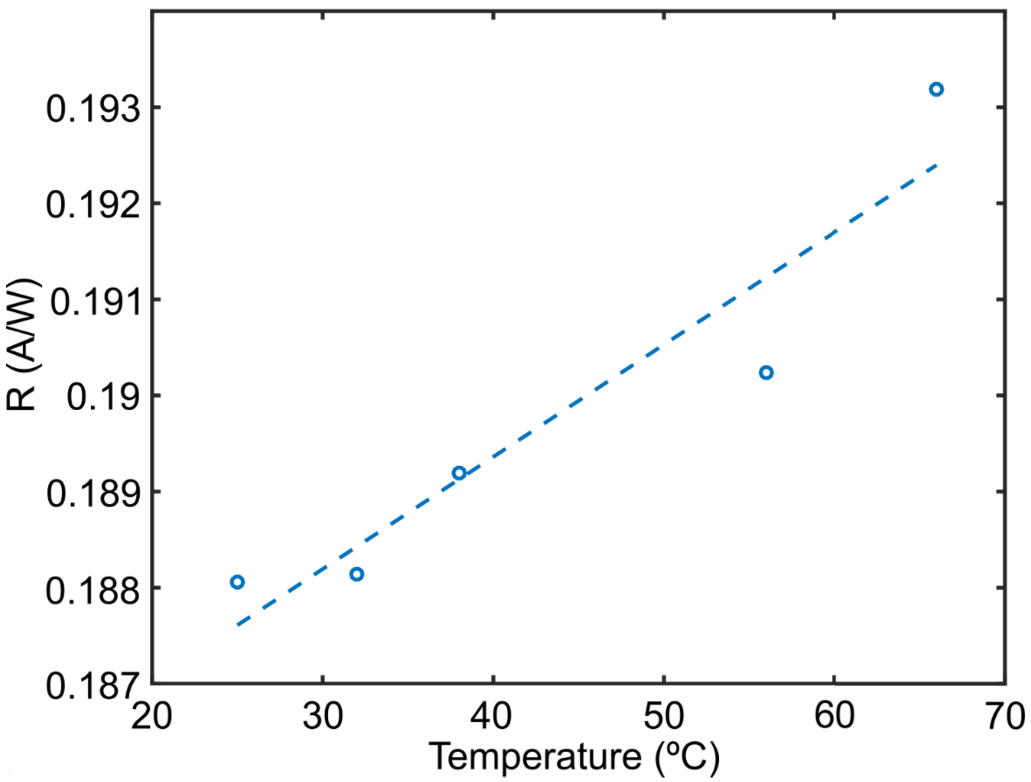

Figure 3. The responsivity of black silicon photodiode as a function of temperature at 220 nm. Circles show experimental values and the line is linearly fit to the data.

4.2 Dark current of black silicon photodiodes

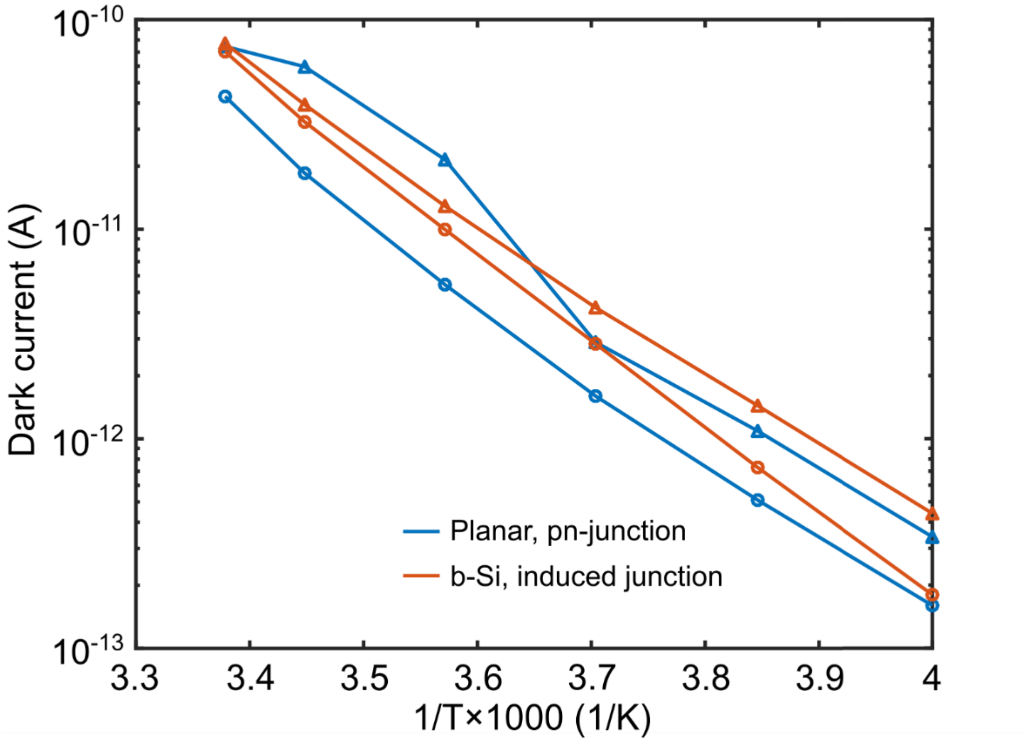

Figure 4. The dark current as a function of temperature at 100 V reverse bias. Red curves are from two different black silicon photodiodes and blue curves are from two planar pn-junction photodiodes. Below 250 K data is omitted because the values were limited by noise from the measurement setup.

The temperature dependency of the dark current in planar and b-Si photodiodes is shown in Figure 4. It is similar in both photodiode types. The activation energy E_a ($I=k*exp(-qE_a/kT)$) is around 0.77 eV±0.1eV. Based on these results, it seems that the junction type has a negligible effect on the temperature dependency of dark current, which makes sense as large fraction of the dark current is arising from generation occurring in the depletion region. Furthermore, the determined activation energy here is in typical range compared to values reported in the literature[11] for silicon detectors. Measurements were limited by noise from the measurement setup below 250 K and therefore those temperatures are not shown.

5. CONCLUSIONS

The dark current and its temperature dependency of black silicon induced junction and planar pn-junction photodiodes were found to be essentially bulk properties of silicon, when similar guard ring structure, starting bulk material and processing tools were used. Thus, the noise level is not increased by black silicon treatment or by using induced junction. Similarly, temperature dependency of responsivity in black silicon induced junction photodiodes can be explained largely by temperature dependency of silicon absorption coefficient. The responsivity has very small temperature dependency in visible range, and the relatively change is less than 0.3×10^{-4} /K. The relative change of responsivity with temperature is larger in NIR, up to 6×10^{-3}/K at 1100 nm, and in UV region ~10^{-3}/K. Consequently, our results prove that the temperature dependent characteristics of black silicon photodiodes behave essentially similarly than in conventional photodiodes indicating that the improved SNR is maintained also at temperatures other than RT.

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