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Integration of Si-based UV-photodiodes into a 0.35 µm modular CMOS platform

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Abstract

Ultraviolet (UV) sensitive Silicon based photodiodes integrated into a high-voltage modular 0.35 µm CMOS technology are presented. An optimized sensitivity higher than 0.1 A/W is obtained for the relevant UV-B (λ = 280-320 nm) and UV-A (λ = 320-380 nm) spectral range for n-on-p and p-on-n photodiodes. In addition, a special UV block layer can be integrated for dark current compensation without further mask count. The photodiodes are stable during long time UV light exposure.

Key words: Ultraviolet (UV), CMOS, Silicon photodiode, 0.35 µm technology, UV-stable

CMOS Integrated UV-Photodiodes

On-chip photosensitive diodes are used for integrated sensor solutions. For this purpose Silicon based photodiodes can detect light from the near-infrared to the visible spectral range [1]. An optimized process allows further detection of light in the relevant ultraviolet (UV) spectral range. Application of UV sensor technology is widespread for chemical and medical applications. While UV light may be used for applications in advanced lithography such as deep UV and extreme UV lithography [2], in mobile applications it can be used for UV index sensing. For this later application the target wavelength range of UV-A and UV-B is of interest.

Several approaches exist for UV light analysis based on Silicon-Carbide (SiC) [3] or thin film technology [4]. However, a low cost as well as repeatable and stable process is an advantage of using integrated Si CMOS based UV sensors. This may be implemented with a simple front-side illumination (FSI) approach and quantum efficiency well above 50 %. Additionally, mixed signal processing allows analog to digital interfacing with further signal amplification.

Integration of UV photodiodes into a modular high voltage Silicon CMOS platform is thus advantageous compared to other UV sensor technologies.

Optimization of UV Response

We report on the performance of two UV sensitive device types of n-on-p and p-on-n pn-junction photodiodes formed by standard CMOS implant steps. By forming a UV light transparent optical window and reducing the UV reflectivity with Anti-reflective coating (ARC) of the standard silicon diode surface, it is possible to achieve highest UV responsivity above 0.2 A/W, and quantum efficiency > 60 % at the target wavelength range of 300 to 380 nm (UV-A, UV-B). This optical window is achieved by removing the backend dielectric stack above the optical active photodiode area.

The responsivity curve of a UV photodiode in 0.35 µm technology with the optical window and one additional mask layer compared to the standard CMOS process flow can be seen in Figure 1 (red curve) for an n-on-p device. The presented photodiode may detect light in the visible as well as in the near infrared spectral range.

The sensitivity is measured on wafer level using a solarization stable optical fiber, a wide bandwidth optical light source and a monochromator setup to sample light with only one tunable wavelength and a bandwidth with typical 2 nm. The sensitivity is determined from the measured photocurrent and by using a calibrated standard with known sensitivity by relating the measured current to the final sensitivity data using equation 1

$$S_\lambda = \frac{I_\lambda}{I_{ref}} S_{\lambda,ref} \, . \ (1)$$

Here, S_λ is the wavelength dependent sensitivity, I_λ is the wavelength dependent photocurrent and $S_{\lambda,ref}$ is the known sensitivity of the reference sensor as well as the current I_{ref} of the reference diode.

Alternatively, the complete removal of the backend dielectric stack may be replaced by a simple removal of the UV-nontransparent top Silicon nitride of the CMOS passivation. By this approach one mask layer can be saved with the expense of lowered sensitivity to 0.1-0.15 A/W in the target UV-A/UV-B wavelength range. The results of this partially removed passivation (PRP) are compared in Figure 1 with the optical window approach described above. A schematic cross-section of the n-on-p photodiode structure can be seen in Figure 2.

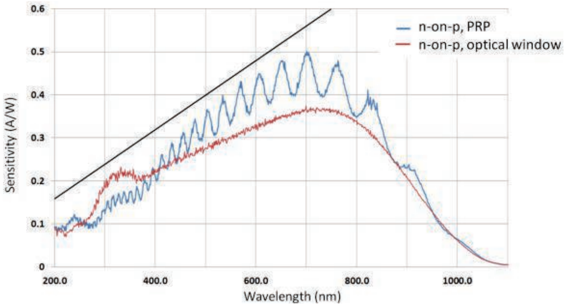

Figure 1. Comparison of the spectral sensitivity of the n-on-p photodiode with either an UV-ARC layer and an optical window (red curve) or a partially removed passivation (blue curve).

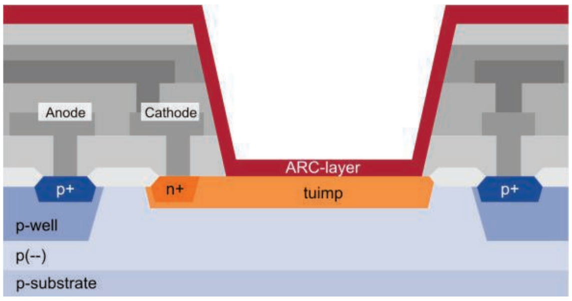

Figure 2. The schematic cross-section of the n-on-p device that has a UV-ARC layer for improved sensitivity results.

In general, n-on-p photodiodes may give an additional advantage due to the positive charge that may occur during processing in the silicon cap oxide [2,5]. This charge is known to create an electrical field to direct hole minority carriers from the surface into the depletion zone. Thus the n-type top implant layer is advantageous compared to p-on-n device geometry.

On the other hand, the placement of a p+ implant into an n-well forms a stacked photodiode into the p-type substrate that can be used to suppress near infrared and part of the visible light spectrum by photodiode design.

Figure 3 shows a basic device cross-section of the photodiode and Figure 4 shows the results of the optical characterization. Depending on the contact choice the photocurrent is highest in the range of 200 to 600 nm if the current is extracted from the top anode junction. This relates to the p-type doping to n-well junction and the low photon penetration depth of light with low wavelength, as well as the weak absorption of photon with higher wavelength in this Silicon region. Consequently, the lower n-well to p-type substrate will cut away the red and near infrared part of the light spectrum.

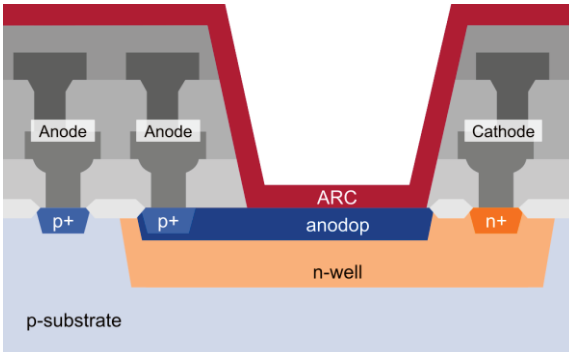

Figure 3. The schematic cross-section of the p-on-n device having a UV-ARC layer for improved sensitivity results is shown. The stacked design of the photodiode diode results in the presence of two anode terminals.

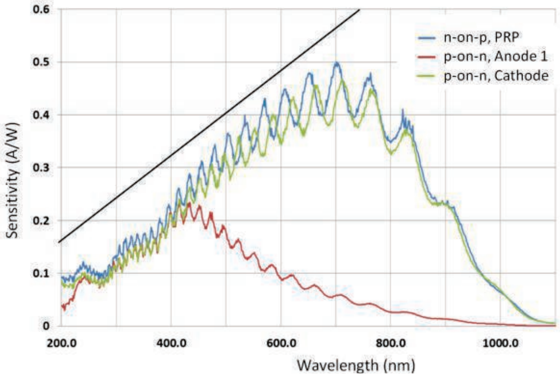

Figure 4. A comparison of sensitivity data for the n-on-p (blue curve) and p-on-n (green and red curve) photodiodes is shown. The current for the stacked photodiode is measured at the top anodop to n-well junction (red curve) and at the n-well junction (green curve).

Modular process option for multichannel sensing

An advantage of the discussed modular process technology is to enable the alternative implementation of IR-enhanced (λ= 850 nm), red-enhanced (λ= 650 nm) or blue-enhanced (λ= 405 nm) photodiodes in one sensor layout depending on the chosen ARC layer thickness.

Furthermore, an option for the UV sensitive photodiode may be adding additional block or cut-filter layers on top of the photo-sensitive device. This layer can be added to the CMOS process with no extra mask cost by means of a thin poly-silicon layer.

This option may be used for dark current compensation in combination with a UV sensitive device in order to block all light generated from high energy photons with wavelength below 400 nm. A typical transmission curve for this filter layer can be seen in Figure 5.

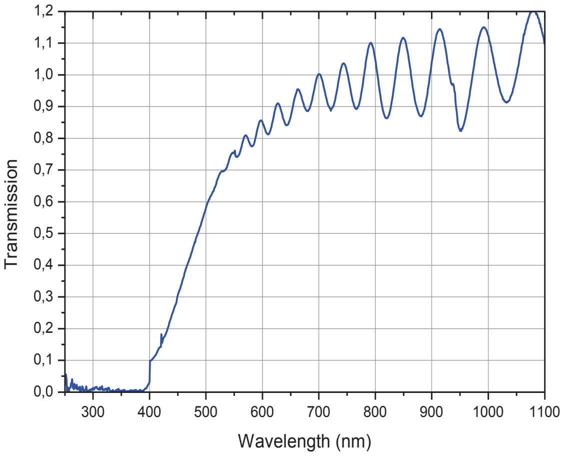

Figure 5. The transmission versus wavelength for a poly-silicon UV filter layer is plotted. The estimated transmission is obtained from the ratio of sensitivity with and without filter and is neglecting additional reflection losses present.

Dark current compensation and reference device formation

Silicon based pn junction offers very low leakage current due to the high passivation efficiency of surface in CMOS technology. The dark current of the n-on-p device is shown in Figure 6 for different temperature conditions, showing very low leakage current for test structures with a size 100x100, 250x250 and 500x500 µm^2. This gives rise to an approximated area junction leakage of <$1\cdot10^{-3}$ fA/µm^2, measured at room temperature and <0.1 fA/µm^2 at 85°C.

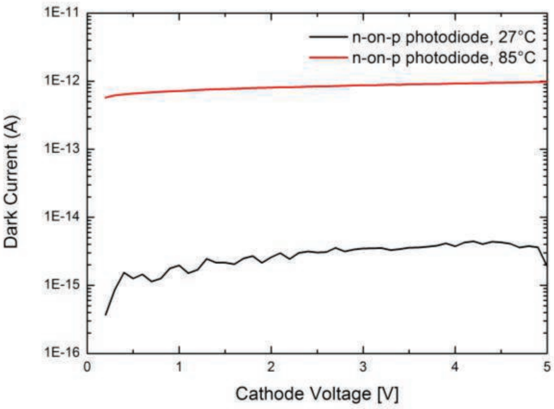

Figure 6. The figure shows the current-voltage characteristics of an n-on-p photodiode with area of 100x100 µm^2 at a measurement temperature of 27 and 85 °C.

In addition to the UV sensitive photodiode, special dark current compensation diodes are investigated whereas the structure has to be matched to give similar dark current characteristics at different operating conditions. A special approach to suppress the UV spectral range up to 400 nm is presented by means of a UV block layer deposited within the CMOS process that can be used to form a reference device. For this purpose a metal shielding on top of the active diode area can be used

Ultraviolet stability

Wafer level UV stability tests are performed using a high intensity UV lamp with a UV intensity of 18.5 mW/cm^2 at 254 nm and measuring the UV sensitivity of the photodiode after a predefined exposure times using equation 2

$$Exposure = P \cdot t = 18.5\, mW / cm^2 \cdot t\,, \quad (2)$$

where t is the overall exposure time and P is the lamp power per surface area.

As a measure for the UV stability the sensitivity change defined by equation 3 is tracked as a function of the exposure time

$$\frac{\Delta S}{S} = \frac{S_\lambda - S_\lambda(0\,s)}{S_\lambda(0\,s)}\,. \quad (3)$$

Here S_λ (0 s) is the sensitivity of the photodiode with no intentional exposure to UV light.

For exposure levels up to 0.33 kJ/cm^2 a signal change of 5 % for the n-on-p device is observed as shown in Figure 7. Similar results with a change of less than 5% are observed in case of p-on-n device structures. The exposure of up to 0.33 kJ/cm^2 relates to approximately one year (12h/day) in midday sun with 25 µW/cm^2 at room temperature.

While unstable response in Vacuum-UV are reported for Silicon diodes with light exposure of 193 nm and exposure levels of 0.1 to 10 kJ/cm^2 [5], we see a stable UV sensitivity for the UV exposure described here. In addition, a thin oxide passivation layer on the front side of the photodiode will effectively passivate the Silicon surface regarding the optical range of UV-A and UV-B.

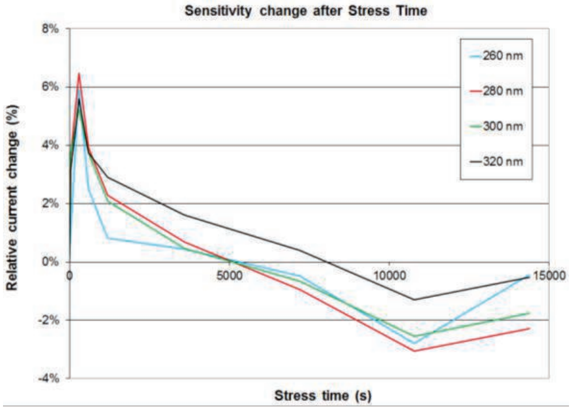

Figure 7. Relative change of the UV response as a function of UV light exposure stress time for the n-on-p photodiode. The sensitivity change at 4 different wavelengths in the UV-A and UV-B spectral range is compared. For the two diode types the change in the sensitivity after 5 hours high intensity UV exposure is below 5 %.

Summary

In summary, we have shown the integration of Si-based UV photodiodes into a 0.35 µm technology and discussed different technology challenges for the implementation. We have found excellent process compatibility for applications requiring high sensitivity of up to 0.2 A/W, and UV stability within the relevant application range with variation less than 5 % for long time UV exposure.

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