OBSEVED SIMILAR BEHAVIOUR OF a-Si:H P-I-N PHOTODIODE AND RETINA RESPONSE

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ABSTRACT
Epiretinal and subretinal prosthesis implants, composed mostly of silicon CMOS neuromorphic chips have recently been proposed. In this paper, we present measurements that detail the similarities between some mammillae retinal responses, monitored by electroretinography (ERG) and those of a-Si:H p-i-n photodiode (PD) response. The PD response on simultaneous voltage and light pulses has a similar shape as retinal layers response. The characteristic shape of PD response, ascribed here to trap states, is analyzed. The optimal parameters (amplitude, duration, waveform and frequency) and threshold voltages of the a-Si:H p-i-n photodiode responses were identified. The voltage pulse influence on photodiode response can be compared with activities of bipolar cells in retinal response. Previously described PD behaviour suggests potential use of a-Si:H p-i-n PD as active pixel in retinal implant.

KEY WORDS
a-Si:H, Defects, Photodiode, ERG, Retina

1. Introduction
Eye diseases, such as retinitis pigmentosa (RP) and age-related macular degeneration (AMD) are today’s main causes of blindness. Various research groups have proposed the retinal prostheses to restore useful eyesight, with specific attention to epiretinal and subretinal prosthesis implants [1]-[7]. In most cases, retinal implants were based on active microphotodiode array (MPDA) CMOS circuitry-neuromorphic chips. In order to understand the impact of retinal stimulus on behaviour of characteristic features in recorded ERG patterns better, many different studies, mostly on isolated mammillae retinas, were obtained [8]-[12]. In these papers different light sources, wavelengths, pulse durations (frequencies) of photo and voltage stimulus and their effect on negative a- and positive b1- and b2-waves were studied. In [13] and [14], we investigated a-Si:H p-i-n PD responses on various voltage and light excitations. In this paper, the a-Si:H p-i-n photodiode response to light and voltage pulses is analyzed and similarities to response of mammillae retina are observed. Other authors have described mammillae retina response monitored by electroretinography (ERG). The optimal parameters (amplitude, duration, waveform and frequency), threshold voltage and response latencies of the a-Si:H p-i-n photodiode responses on simultaneous electrical and light stimulation were found. The photodiode response and mammillae ERG waveforms appear similar.

We report here a new method for generating the specific shape response of a-Si:H p-i-n PD sensor on visible light. Our results show the possibility of further reduction of circuits’ complexity, working at a very low operation bias of 2V and less. This could also contribute to better retinal implants’ image quality realized in a-Si:H thin-film technology and may be used for instrument calibration in optoelectronic devices and as a part of electronic medical devices in general.

After a brief description of the experimental details in Section 2, obtained results are presented and discussed in Section 3. Finally, the conclusions are given in Section 4.

2. Device fabrication and measurements
The a-Si:H p-i-n structure was deposited on a transparent conductive oxide (TCO) coated glass from undiluted SiH₄ by plasma-enhanced CVD as described in [13]. The thicknesses of the n-type, i-type and p-type layers were 5 nm, 300 nm and 5 nm, from top to the bottom, respectively. The n-type layer was made by adding phosphine and the p-type by adding diborane to the gas mixture. The back contact was aluminium deposited by the evaporation. The area of the pixel was 0.28 cm². The basic device characterization and experimental system are described in more details in [13] and [14]. Photooillumination was obtained through the bottom p-type layer. The transient response of a-Si:H device was measured as a response to the simultaneous pulses of light and bias voltage.

Measurements were carried out at the room temperature. Multicolor LED lamps were used in the experiments, emitting at 470 nm, 565 nm, and 624 nm for blue (B),
Fig. 1. PD responses to simultaneous blue light and voltage pulses of 0.5 ms duration ($T_p$) for different voltage pulse amplitudes (dV) from 0.1 to 0.5 V.

green (G) and red (R) light, respectively. The characteristic pulse widths in our experiments (0.5 - 3 ms) are in accordance with relevant values used in measurements of other authors obtained on retina and described in [9]. Simultaneous response on voltage and light pulse was measured on a-Si p-i-n photodiode at 2V reverse bias voltage. The voltage pulse amplitude was changed from 0.1 to 1 V for all wavelengths. When the light pulse was on, the voltage pulse was biased forward. The same response behaviour was observed in reversed mode, too. The measurement set-up was previously described in details [13].

3. Results and discussion

Fig. 1 shows the pulse response measurement on the a-Si p-i-n sample at voltage pulse amplitude from 0.1 to 0.5 V and 0.5 ms pulse duration with period of 3 ms at 470 nm blue light pulse. As shown in the figure, the shape of responses changes with voltage amplitude. For voltage amplitudes from 0.1 to 0.2 V, initially the voltage (electric field) impact on response prevails under influence of light. The positive amplitudes ($p_1$) are voltage dependent as shown in Fig. 1. This is followed by negative amplitude ($n_1$). Subsequently, the second, positive amplitude ($p_2$) in measured response is observed (Fig. 1). For higher voltage amplitudes, above 0.2 V for blue light, the optical generation has a small influence and electric field influence prevails. This analysis groups responses in two distinct shapes a) characteristic and b) standard. The same observation is valid for all basic colors (R, G, B) and for their superposition (RGB). Standard responses are similar to our results from previous papers [13], [14] while characteristic responses, with quite different shape show similarities with retinal signals which would be discussed later.

Fig. 2. PD responses to simultaneous voltage and blue light pulses and corresponding energy levels.

Trap states in a-Si:H are responsible for the specific shape of a-Si:H p-i-n photodiode response as described in the following analysis. If light and forward pulses are applied simultaneously at 2 V reverse bias, initial electric field decreases as well as space charge region width due to externally applied voltage. Dangling bond states in D$^0$ band above E$_F$ trap electrons and become D$^+$ in vicinity of i-n junction. Holes trapped at p-i junction below E$_F$ ($D^0 \rightarrow D^+ + e^-$) are slower than electrons and do not contribute to photocurrent as much. In the same time the photogenerated charge carriers reduce the space charge density growth due to the dangling bonds and consequently the electric field in the central part of the i region. This appears as a decrease of bias voltage and is evident in first positive amplitude ($p_1$) in Fig. 1. The calculated activation energies of dangling bonds, as described in [14] and [15] using methods from [16], [17] and [18], for red, green, blue and red-green-blue light within first 0.02 ms of photodiode response, are 0.443 eV, 0.433 eV, 0.389 eV and 0.409 eV below the conduction band edge, respectively. Due to blue light illumination, photo-generated electrons are trapped in vicinity of p-i junction in D$^0$ states at energy of 0.389 eV below conduction band shown in Fig. 2. In the following time interval of 0.2 ms the current increases due to direct photo-generations and electrons emission from the trap states at around -0.475 eV. The photovoltage/current reaches local minimum ($n_1$) when D$^+$ states in vicinity of p-i junction are nearly all empty. When light is turned off and reverse bias is increased, photovoltage/current rises suddenly ($n_1$) due to emission of electrons from shallow states at n-i junction. The depletion layer widens and new trap states are activated at energies of around -0.385 eV near n-i junction. At this stage photo-generated carriers at the p-i junction contribute to the current before they recombine. After next 0.03 ms, the recombination prevails and the photo voltage current decreases. The trap states at energies of 0.496 eV are activated. At the p-i junction, filled D$^-$ states trap electrons and become D$^0$;
Fig. 3. PD responses to simultaneous blue light (B) and voltage pulses of 0.1 V voltage amplitude (dV) and different pulse durations (Tp) from 0.5 to 3 ms. Consequently, the local electric field is decreased. Current decrease stops when all traps are filled.

When photovoltage/current reaches second local maximum (before p2) the activation of shallower states at -0.42 eV can be described as the emission and at third local maximum (p2) at -0.496 eV as capture of free carriers. Deeper states at -0.538 eV contributes to the tail in the current response shown in Fig. 1.

Similar behaviour is observed in all measurements for all monochromatic R, G, B and chromatic RGB light illuminations.

In order to determine the influence of photo-generated carriers on pulse response, pulse durations were varied from 0.5 to 3 ms. Fig. 3 shows the a-Si:H p-i-n responses to blue light pulses and voltage pulses from 0.5 to 3 ms duration, with a voltage pulse amplitude of 0.1 V. These values are in line with values from [3], where they were chosen, because stimulus impulses longer than 0.5 ms can target bipolar cells in the retina. With the pulse duration increase, the response latency increases, too. The negative, n1-wave and the positive, p2-wave amplitudes also increase. Concurrently, the sustained negative potential rises from approximately -2.3 to -1.3 V.

Fig. 4 shows the PD responses on the simultaneous voltage and R, G, B, RGB LED light stimuli. The voltage pulse amplitudes for R, G, B and RGB were 0.3, 0.1, 0.1 and 0.5 V, respectively.

Dependently on shapes of presented effect, the threshold voltage of white light, obtained as a superposition of basic light sources, R, G and B, is equal to the sum of particular thresholds. This behaviour can be expressed via following relation:

\[ V_{th_{RGB}} = V_{th_{R}} + V_{th_{G}} + V_{th_{B}} \]  

(1)

where, \( V_{th_{R}}, V_{th_{G}}, V_{th_{B}} \) are threshold voltages at which the individual responses show their characteristic response shape.

Moreover, the simultaneous light and voltage pulse response performances of the a-Si:H p-i-n PD under different operating voltage and light excitation conditions were compared to ERG and VEP responses measured on humans [3], several other mammillae (mice [9], dogs [10] and rabbit [4]) and Drosophila [12] found in the literature. We observed that the responses of a-Si:H p-i-n PD, described in this paper, have the similar waveform as the ERG in Drosophila, [12] and mammillae flash photopic ERG [19, 20]. The best similar properties regarding pulse duration (0.3 – 0.5 ms) and waveforms can be observed with the electrical pulses evoked in mice [9] and rabbits’ [11] retinal responses.

The a-Si:H p-i-n photodiode response shows a Type 1 waveform for white light illumination and Type 2 for basic color illumination at lower voltage amplitudes and pulse duration. These results correspond to the higher stimulus threshold amplitudes described in [11].

The major observed similarity between photodiode and retinal responses lies in the next. In photodiode response the negative n1 amplitude is evident as a consequence of simultaneous forward voltage (depolarizing) and light pulses. Similarly, the a-wave is negative in polarity and is the first major component of ERG. The generator of the a-wave mainly is at the level of the photoreceptors and post-receptoral contributions from the OFF component at lower intensities [20]. The positive p2 amplitude in photodiode response is a consequence of simultaneously
applied light and reverse voltage pulses. The b-wave component of ERG would be generated as a result of the synchronized activation of the ON-depolarizing bipolar cells (ON-DBC) [19, 20]. The oscillations as oscillatory potentials are also present in photodiode response at higher frequencies. The more precise retinal activities record multifocal ERG (mfERG). The inner retina (i.e., ganglion cells and some amacrine cells) activities (depolarization of cells) mainly contribute to the p2 in second-order kernel (K2.1) waveform. Oscillatory potential originate from the inner retina. This is similar to p2 and the tail in PD response after the light and voltage are turned off (increased reverse voltage). Oscillations originate from hopping and trapping processes. Removing the influence of inner retina, the mfERG is mainly a combination of the contribution from the outer retina, cones and the ON- and OFF-bipolar cells. These activities were registered by second-order kernel, as described in [21] and [22]. After these studies, the hyperpolarization of the OFF-bipolar cells occurred in response to an increase in light. This corresponds to positive amplitude (p1) in PD response, as a contribution of simultaneously forward voltage and light turned on. Depolarized ON-bipolar cells contribution is just before the peak of n1 and the initial part of p2. The ON-bipolar cells contribution corresponds to the photodiode integration time during simultaneous light and voltage pulses. The OFF-bipolar cells recovered (depolarized) before the peak of p2. The depolarization of the OFF-bipolar cells and the time in which the ON-bipolar cells contribution reached the peak of its recovery corresponds to sudden simultaneous increases of reverse voltage on the photodiode and a light turn off. Our observation is that the amplitude peak to peak from n1 to p2, decreases with frequency, as described by [23]. The observed similar behaviour of a-Si:H p-i-n photodiode and retinal layers will be examined in the future work.

3. Conclusion

The characteristic shape of a-Si:H p-i-n photodiode response to simultaneous voltage and light pulses at low bias voltages are obtained. The trap states energy levels are calculated and their influence on photodiode response is analyzed. Several behavioural similarities of retinal electrical response to a flash of light and the a-Si:H p-i-n photodiode response to simultaneously voltage and light pulses are observed. The parameters (amplitude, duration, waveform and frequency), threshold voltage and latency of PD response on simultaneous voltage and light pulses show similar properties as retina response. The voltage pulse in photodiode excitation has the analogous function as that associated with the activation of bipolar cells in the retina. The threshold voltages at which the characteristic photodiode response shape arises are found for red, green, blue and red-green-blue wavelengths, respectively. The photodiode can represent only one small area of retina. Further investigation is necessary in order to clarify whether the obtained result can contribute to development of retina model and new colour detection sensors. The results show potentially further reduction of circuit complexity, working at very low operation voltages of 2V and less, realized in a-Si:H thin-film technology.

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