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Characterization of a-Si:H P-I-N photodiode response

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Abstract: The a-Si:H p-i-n photodiode response due to simultaneous voltage and light pulses has a characteristic shape similar as that of retinal layers response. The characteristic shape of photodiode response, ascribed to trap states, is analyzed and discussed. The amplitude, waveform, latency and threshold voltages of the a-Si:H p-i-n photodiode responses were analyzed in dependence of voltage pulse amplitude and voltage and light pulses duration. The simultaneous stimuli influence on photodiode response has been explained through the excitation of dangling bond in i-layer. Described photodiode response behaviour suggests potential of development of a method for defect characterization and use of a-Si:H p-i-n PD as image sensor.

Keywords: a-Si:H, defects, photodiode, retina

Karakterizacija odziva a-Si:H P-I-N fotodiode

Izvleček: Oblika odziva a-Si:H p-i-n fotodiode pri sovpadnih napetostnih in svetlobnih pulzih je podobna kot odzivu plasti mrežnice. Analizirana in predstavljena je tipična oblika odziva fotodiode pri različnih stanjih pasti. Amplituda, oblika signala, latenca in prag napetosti a-Si:H p-i-n fotodiode je bila analizirana v odvisnosti od amplitude napetostnega pučza in trajanja osvetlitve. Odziv fotodiode pri sočasnem vzbujanju je razložen s pomočjo vzbujanja bingljajočih vezi v plasti i. Opisan odziv fotodiode ponuja možnost razvoja metode karakterizacije defektov in uporabe a-Si:H p-i-n PD kot slikovnega senzorja.

Ključne besede: a-Si:H, defekti, fotodioda, mrežnica

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1. Introduction

It is well known, that the presence of charged defects in the optically active material, which is intrinsic layer (i-layer) in the p-i-n, a-Si:H photodiode reduces the built-in electric field [1]-[4] and consequently the local optical absorption coefficient [5], reduces the free carriers mean lifetime, decreases the response time. The knowledge of the spatial distribution of defects induced by light is important in improving the photodiode performances in order to use it as a detector in active pixel sensor and imaging sensors. The mid-gap states energy levels and their spatial distribution in i-layer and at p^+-i interface can be obtained [6, 7] from the transient dark current and steady-state thermal generation current. Emission of carriers from the p-i and n-i interfaces and thermal generation in i-layer, which is a voltage dependent at low biases, mainly contribute to the dark current. The optical and electronic properties of a-Si:H determine transient current relevance for device application. The recombination via dangling bonds as the main recombination centers and transport through localized states contributes to the transient current as are well described by Fuhs [1] and Dhariwal et al. [2-4]. The influence of deeply-trapped charge on the transient photocurrent has been studied by various authors using the transient photocurrent method TPC and the AC and DC constant photocurrent method CPM [8-10].

The aim of this paper is to study the transient responses and respective time constants after the simultaneous illumination and voltage pulses as well as the influence of dangling bond states on characteristic shape of photodiode response previously observed in [11] in comparison with similar behaviour of retinal response [12]. The optimal parameters (amplitude, duration and waveform), threshold voltage and response latencies of the a-Si:H p-i-n photodiode responses on simultaneous electrical and light stimulation were analyzed and discussed.

The results show the dangling bond states energy levels distributed in range from shallow to deep and activated at low bias voltages and visible pulses illumination, are responsible for characteristic photodiode response shape. Further investigation is needed to develop the method for colour recognition and material characterization.

After a brief description of the devices fabrication and measurements in Section II, the obtained results are presented and discussed in Section III. Finally, the conclusions are given in Section IV.

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 SiH_4 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 cm^2. The basic device characterization and experimental set-up are described in more details in [13] and [14]. Photo-illumination 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. Multicolour LED lamps were used in the experiments, emitting at 470 nm, 565 nm and 624 nm for blue (B), green (G) and red (R) light, respectively. The pulse widths in our experiments (0.5 - 3 ms) are in accordance with relevant values used in measurements of other authors obtained on retina [15].

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 at constant pulse duration for all wavelengths. For the same voltage pulse amplitude, the pulse duration T_a was changed from 0.5 to 3 ms. The concurrent forward voltage and light pulses were applied on a-Si:H p-i-n photodiode at low reverse voltages. The same response behaviour was also observed in reversed mode. The measurement set-up was previously described in detail [13].

3. Results and discussion

Fig. 1 shows the a-Si p-i-n PD responses on the simultaneous voltage and R, G, B, RGB LED light pulses. The voltage pulse amplitudes for R, G, B and RGB were 0.3, 0.1, 0.1 and 0.5 V, respectively and 0.5 ms pulse duration (T_a) with period of 3 ms. As observed and described previously in [11], with increased voltage amplitudes, above threshold voltage for any wavelength, the electric field influence prevails over the optical generation. The responses (basic colours R, G, B and their superposition RGB) show two distinct shapes a) characteristic and b) standard. Standard responses are exponential in nature while characteristic responses, with quite different shapes, are exponential in smallest time intervals and show similarities with retinal signals [11].

The characteristic shape of all responses for given small voltage pulse amplitude and pulse duration is shown in Fig. 1 and Fig. 2. In first time interval the positive amplitudes (p1) is present, which are voltage dependent as described in [11]. After that, is the region of exponential fall to quasi steady-state, negative potential, NP [12, 15]. Next follows sudden fall to negative amplitude (n1) and than the second positive amplitude (p2) before long tail and after that appears wavelength dependent third (p3) positive amplitude (Fig. 1). Increasing the voltage pulse amplitude, at 0.5 ms pulse duration, the photodiode response takes spike shape as shown for blue light illumination in Fig. 2.

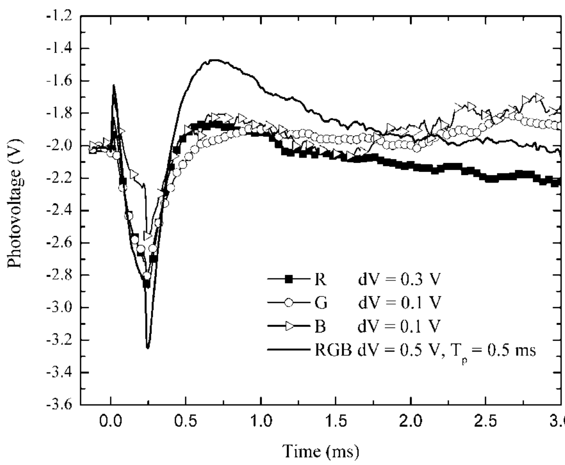


Figure 1: PD responses to simultaneous light and voltage pulses under the illumination of R, G, B and RGB LED. The voltage pulse amplitudes (dV) were 0.3, 0.1, 0.1 and 0.5V, respectively. Pulse duration (T_p) of 0.5 ms was the same in all cases.

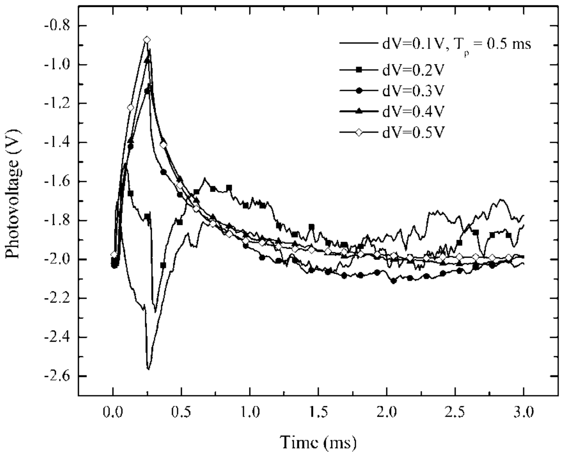
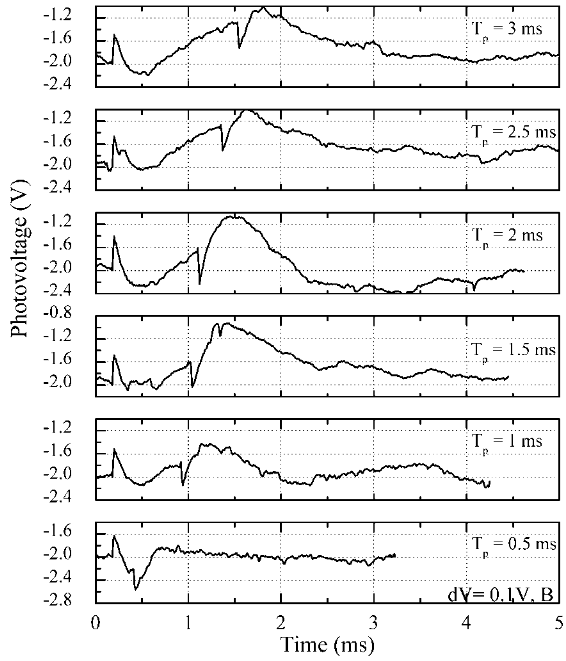
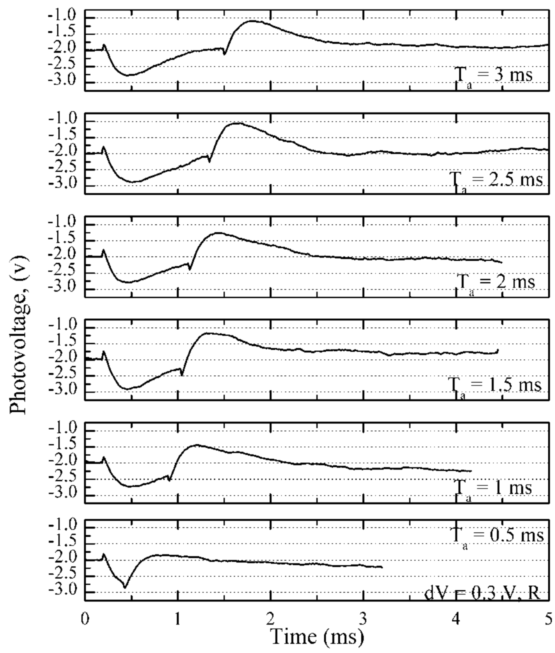


Figure 2: PD responses to simultaneous blue light and voltage pulses of 0.5 ms duration (T_p) for different voltage pulse amplitudes (dV) from 0.1 to 0.5 V.

The detailed analysis of characteristic shapes follows. The threshold voltage at which appears the characteristic photodiode response shape is 0.1 V, for blue and green light, 0.3 V and 0.5 V for red and RGB light, respectively. The peak-to-peak amplitude, defined as difference from positive (p2) and negative (n1) amplitude, is 0.76 V, 0.91V, 1.02 V, 1.73 V for blue, green, red, and RGB light, respectively and it decreases with increased voltage pulse amplitude. The positive response amplitude (p2), in relation to referent reverse bias voltage of -2 V, increases until negative amplitude (n1) and their difference decrease with voltage pulse amplitude. The difference in latency times between p2 and n1 decreases, also. The negative potentials, NP, are -2.23 V, -2.68 V, -2.69 V and -3.03 V for blue, green, red and RGB light, respectively.



a)



b)

Figure 3: PD responses to simultaneous a) blue (B) and b) red light (R), respectively and voltage pulses of 0.1 V and 0.3 V voltage amplitude (dV), respectively and different pulse durations (Tp) from 0.5 to 3 ms.

As shown in the Figure 2, and in the Figure 3 a) and b), the shape of responses changes with voltage pulse amplitude and with pulse duration, respectively.

In order to determine the influence of photo-generated carriers on pulse response, pulse durations were varied from 0.5 to 3 ms with period of 5 ms. Fig. 3.a) shows the a-Si:H p-i-n responses to blue light and voltage pulses from 0.5 to 3 ms duration, with a voltage pulse amplitude of 0.1 V. Fig. 3 b) response to red light and voltage pulse amplitude of 0.3 V.

In examining of the photodiode response as a function of pulse duration, it is evident that the all responses show characteristic shape primarily composed of n1 and p2 peaks. However, at pulse duration over 0.5 ms, there is a large secondary minimum, n0, evident in response as overshoot.

The corresponding n1- and p2- peaks delay times called "latency", signed as *α* and *β*, respectively, are measured from the pulses onset and are shown in Fig. 4 for blue light illumination. The negative peak amplitude, n1, firstly decreases with increased pulse duration from 0.5 to 1 ms and remains quasi constant with further pulse duration increase, as shown in Fig. 4. However, the positive peak amplitude, p2, shows increase. The peaks amplitude difference (p2 – n1), increases for small and decreases for higher pulse durations. Delay times, known as latency, for both peaks n1 and p2 increase for same conditions. The observed negative n0 amplitude shows small changes with pulse duration increase, Fig. 4.

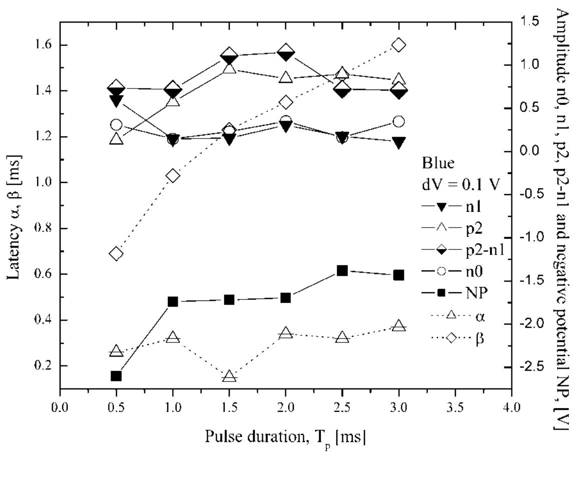


Figure 4: Amplitudes n0, n1, p2, p2-n1, negative potential NP, and latency α, β of n1 and p2 peaks of PD responses to simultaneous voltage and blue light pulses, respectively as a function of pulse duration, Ta = 0.5 ÷ 3 ms.

The characteristic response shape is ascribed to dangling bonds and their effect on transient response of p-i-n a-Si:H photodiode at simultaneously forward voltage and light pulse of visible light at low reverse bias and low frequency as presented and discussed in [11] . The calculated activation energies of dangling bond levels, as described in [14] using methods from [8-9], [16] and neglecting the Poole-Frenkel effect, for red, green, blue and red-green-blue light within time intervals in which the photodiode response is exponential in nature, are shown in Fig. 5.

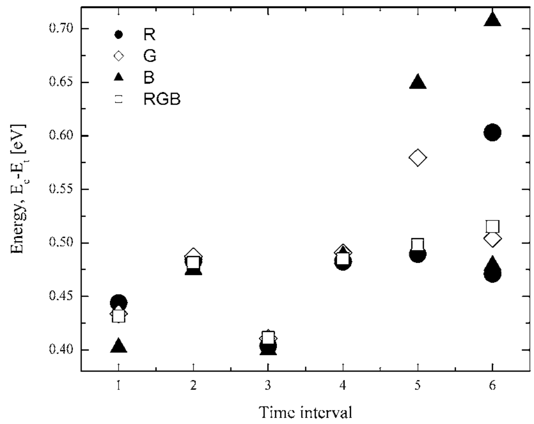


Figure 5: Calculated trap energy levels for PD responses to simultaneous voltage and red, green, blue and red-green-blue light pulses presented in Fig. 1, respectively. The time intervals corresponds to one in which the changes in response shapes occurs and are exponential in nature.

Analysing the measured PD responses it is observed that at small voltage pulse amplitude, less than 0.5 V, in initial time interval, when voltage and light pulses suddenly go on, the voltage (electric field) influence prevails the illumination one. Dangling bond and tail states at energies between 0.4 and 0.45 eV for R, G, B and RGB light illumination, capture the photogenerated free carriers in very short initial time interval. The space charge region reduces and with decreasing electric field, reduces the current. In the second time interval, the exponential rise of photocurrent is present for low voltage pulse amplitude and for all light illuminations used in our experiment. The capture of electrons through the dangling bond at energies below 0.5 eV at p^+-i interface follows the electric field reduction, and consequently the photocurrent reaches the local maximum, or photovoltage corresponding to negative potential, NP. In following time interval present only at pulse durations over 0.5 ms the photocurrent and space charge reduce as recombination takes place through the deeper dangling bonds. For small pulse duration, these photocurrent decreases are not evident. With increased pulse duration, photocurrent increase as an overshoot is present. In the very short next time interval, after the voltage and light pulses are turned off, the current suddenly increases as a consequence of electric field increase, occurs thermal electron emission from shallow states about 0.4 eV and recombination of remaining photogenerated free carriers is negligible. After that follows the long current fall, overshoot, as the consequence of free carriers electrons and holes capture via the deeper states at energies around 0.5 eV. In the last time interval, a long current tail arises from detrapping of carriers from the deep level between 0.5 and 0.7 eV, before steady state. The two energy levels are activated for blue and red light illumination at the end of the tail.

The calculated activation energies of dangling bonds from PD responses (Fig. 2) to simultaneous blue light and voltage pulses with duration (T_p) of 0.5 ms for voltage pulse amplitudes from 0.1 to 0.5 V are shown in Fig. 6. Increasing the voltage pulse amplitude, results in activation of deeper energy levels. At 0.4 V, the two energy levels are involved in response.

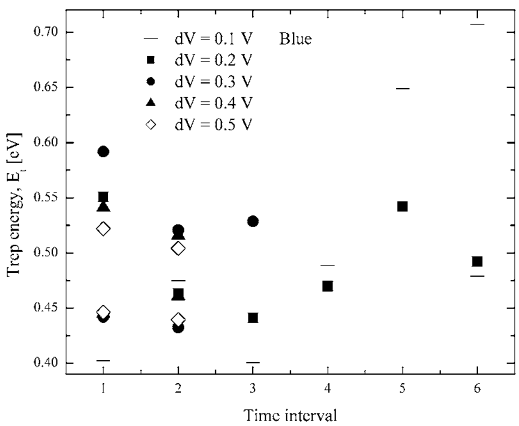


Figure 6: The calculated trap energy levels of PD responses to simultaneous blue light and voltage pulses of 0.5 ms duration (T_p) for voltage pulse amplitude (dV) from 0.1 to 0.5 V.

4. Conclusion

The characteristic shape of a-Si:H p-i-n photodiode response to simultaneous voltage and light pulses at low bias voltages are ascribed to activation of the dangling bond states energy levels. The parameters (amplitude, duration and waveform), threshold voltage and latency of PD response on simultaneous voltage and light pulses are analysed in dependence of voltage pulse amplitude or applied electric field and on duration of excitation pulses. Further investigation is necessary in order to obtain the parameters value for desirable characteristic response shape and to develop new colour recognition sensors and method for semiconductor material characterization.

References

1 W.Fuhs, Recombination and transport through localized states in hydrogenated amorpohus and microcrystalline silicon, J. Non-Cryst. Solids, no. 354, 2008, pp. 2067-2078.

2 S.R. Dhariwal, S.Rajvanshi, Theory of amorphous silicon solar cell (a): numerical analysis, Sol. Energy Mater. Sol. Cells, no. 79, 2003, pp. 199-213.

3 S.R. Dhariwal, S.Rajvanshi, Theory of amorphous silicon solar cell (b): a five layer analytical model, Sol. Energy Mater. Sol. Cells, no. 79, 2003, pp. 215-233.

4 S.R. Dhariwal, M. Smirty, On the sensitivity of open-circuit voltage and fill factor on dangling bond density and Fermi level position in amorphous silicon p-i-n solar cell, Sol. Energy Mater. Sol. Cells, no. 90, 2006, pp. 1254-1272.

5 E. A. Schiff, H. T. Grahn, R. I. Devlen, J. Tauc, S. Guha, "Picosecond Photocarrier Transport in Hydrogenated Amorphous-Silicon p-i-n Diodes," IEEE Trans. Electron Devices, vol. ED-36, pp 2781-2784, Dec. 1989.

6 R.V.R. Murthy, V. Dutta, Underlying reverse current mechanisms in a-Si:H p+-i-n+ solar cell and compact SPICE modeling, J. Non-Cryst. Solids, no. 354, 2008, pp. 3780-3784.

7 S.A. Mahmood. M. Z. Kabir, Modling of transient and steady-state dark current in amorphous silicon p-i-n photodiodes, Current Appl. Phys., no. 9, 2009, pp. 1393-1396.

8 C. Main, Interpretation of photocurrent transients in amorphous semiconductors, J. of Non-Crystalline Solids, 299-302, 2002, 525-530.

9 C. Main, S. Reynolds, I. Zrinščak, A. Merazga, Comparison of AC and DC constant photocurrent methods for determination of defect densities, J. of Non-Crystalline Solids, 338-340, 2004, 228-231

10 A. G. Kazanskii, K. Yu Khabarova, E. I. Terukov, Modulated photoconductivity method for investigation of band gap states distribution in silicon-based thin films, J. Non-Cryst. Solids, no.. 352, 2006, pp. 1176-1179.

11 V. Gradišnik, Observed similar behaviour of a-Si:H p-i-n photodiode and retina response, In Proc. of the 7th IASETD International Conf. on Biomedical Engineering, BioMed 2010, Innsbruck, Austria: IASTED, 2010, pp. 176-180.

12 S. G. Rosolen, F. Rifaudiere, J.-F. Le Gargasson, M. G. Brigell, Recommendations for a toxicological screening ERG procedure in laboratori animals, Doc. Ophthalmol., 110(1), Oct. 2005, 57-66.

13 V. Gradišnik, M. Pavlović, B. Pivac, and I. Zulim, Study of the color detection of a-Si:H by transient response in the visible range, IEEE Trans. Electron Devices, 49(4), 2002, 550-556.

14 V. Gradišnik, M. Pavlović, B. Pivac, and I. Zulim, Transient response times of a-Si:H p-i-n color detector, IEEE Trans. Electron Devices, 53(10), 2006, 2485-2491.
15 T. M. O'Hearn, S. R. Sadda, J. D. Weiland, M. Maia, E. Margalit, and M. S. Humayun, Electrical stimulation in normal and retinal degeneration (rd1) isolated mouse retina, Vision Research, 46(19), 2006, 3198-3204.
16 A. Merazga, H. Belgacem, C. Main, S. Reynolds, Transient photoconductivity, density of tail states and doping effect in amorphous silicon, Solid State Communications, 112, 1999, 535-539.

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