THIN FILM COLOR DETECTORS BASED ON AMORPHOUS SILICON

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Keywors: optoelectronics, semiconductors, color detectors, RGB colors, Red Green Blue colors, thin film technologies, a-Si:H, Hydrogenated amorphous Silicon, PIIIN structures, Positive-Intrinsic-Intrinsic-Intrinsic-Negative structures, two-terminal structures, PIN-PINIP structures, Positive-Intrinsic-Negative-Positive-Intrinsic-Negative-Intrinsic-Positive structures, PINIP-PIN structures, Positive-Intrinsic-Negative-Intrinsic-Positive-Positive-Intrinsic-Negative structures, three-terminal structures, TFA sensors, Thin-Film-on-Application-specific-integrated-circuits sensors, PECVD, Plasma-Enhanced Chemical Vapor Depositions, numerical modeling, TCO, Transparent Conductive Oxides, bipolar biases, forward biases, reverse biases

Abstract: The operational principle of two-terminal and three-terminal three-color detectors with the a-Si:H-based multi-layer multi-bandgap structures is investigated. Two different approaches (the two-terminal and three-terminal approach, which lead to either unipolar or bipolar bias-controlled three-color detection, are described and evaluated in terms of spectral response, rejection ratio and color suppression with regard to illumination intensity and bias-light. For the two-terminal PIIIN structure, numerical simulation results showed strong negative correlation between color separation and bias-light sensitivity, i.e. the better the color separation the worse insensitivity to bias-light and stronger non-linearity with illumination intensity. For the three-terminal PIN/PINIP and PINIP/PIN structures, the thicknesses of the individual layers were first optimized for the detection of the fundamental chromatic components using the numerical simulator and afterwards fabricated and characterized.

Amorfnosilicijevi tankoplastni detektorji barv

Ključne besede: optoelektronika, polprevodniki, detektorji barv, RGB barve rdeča zelena modra, tehnologije tankoplastne, a-Si:H silicij amorfni hidrogeniziran, PIIIN strukture pozitivno-notranje-notranje-notranje-negativno, strukture dvo-terminalne, PIN-PINIP strukture pozitivno-notranje-negativno-pozitivno-notranje-negativno-notranje-pozitivno, PINIP-PIN strukture pozitivno-notranje-negativno-notranje-pozitivno-pozitivno-notranje-negativno, strukture tro-terminalne, TFA senzorji tankoplastni na vezjih integriranih aplikacijsko specifičnih, PECVD nanosi CVD plazemsko izboljšani, modeliranje numerično, TCO oksidi transparentni prevodni, točke delovne bipolarne, točke delovne propustne, točke delovne zaporne

Povzetek: Prispevek obravnava delovanje dvokontaktnih in trikontaktnih trobarvnih detektorjev, ki temeljijo na večplastnih strukturah iz amorfnega silicija. Dvokontaktni pristop zaznava vse tri barve s spreminjanjem zunanje napetosti reverzne polaritete, trikontaktni pa s spreminjanjem zunanje napetosti obeh polaritet. Barvno zaznavanje smo za oba pristopa ovrednotili s spektralno občutljivostjo, rejekcijskimi faktorji in faktorji barvnega dušenja v odvisnosti od intenzitete osvetlitve in dodane osvetlitve. Za dvokontaktno PIIIN strukturo so numerični simulacijski rezultati pokazali močno negativno korelacijo med kvaliteto ločevanja barv in neobčutljivostjo na dodano svetlobo. Z izboljšano kvaliteto ločevanja barv torej izgubljamo na neobčutljivosti na dodano svetlobo. Hkrati postaja spektralni odziv PIIIN strukture v odvisnosti od intenzitete osvetlitve vedno bolj nelinearen. Za trikontaktne PIN/PINIP in PINIP/PIN strukture smo debeline posameznih plasti optimirali za detekcijo osnovnih kromatskih komponent s pomočjo numeričnega simulatorja, jih izdelali in okarakterizirali.

1. INTRODUCTION

Hydrogenated amorphous silicon (a-Si:H) thin film optoelectronic devices are not only easily applicable in intelligent image thin-film-on-application-specific-integrated-circuits (TFA) sensors /1/, but they can also be simply integrated upon amorphous, poly- or monocrystalline readout electronics /2,3/. The optoelectronic properties of a-Si:H based films can be changed by deposition parameters of plasma-enhanced chemical vapour deposition (PECVD) process and by modifying the optical gap by the addition of carbon or germanium atoms in the plasma during the deposition. Such an approach enables detection from ultraviolet to the infrared /4,5/. High photosensitivity in the visible light spectrum, homogeneous deposition over large areas by PECVD, and low-cost fabrication make a-Si:H and its alloys a promising candidate for color detectors /6/. In multi-layer a-Si:H based structures for detection of two, three or more colors, spectral response is bias-controlled. Since all the signals (e.g. red, green and blue (RGB)) are bias-controlled at the same spatial detector position without the need of optical filters, the color-moiré effect can be prevented. The possibility of producing large area photosensing arrays makes a-Si:H-based devices even more attractive.

Recent advances in the two-terminal a-Si:H based three-color detectors exhibit the potential of these devices for the color sensor arrays. Unresolved speed limitation of the two-terminal transparent conducting oxide (TCO)/NIPIIN/metal detectors /7/ speaks in favour of the alternative two-terminal TCO/PIIIN/metal detectors /8,9/. In order to achieve bias-controlled spectral separation of fundamental chromatic components RGB, the PIIIN structures need to be band-gap profiled. To examine such an approach, the ASPIN numerical simulator is used.

Beside two-terminal devices, a family of three-terminal three-color detectors based on stacked a-Si:H based structures is theoretically and experimentally investigated. The detectors have the structure

TCO/PI$_1$N/TCO/PI$_2$NI$_3$P/metal or TCO/PI$_1$NI$_2$P/TCO/PI$_3$N/metal. Using the ASPIN numerical simulator, device physics of different design concepts is analyzed and presented. Optimization criteria deduced from simulation and experimental results and their comparison are investigated and discussed.

2. NUMERICAL MODELING

The ASPIN computer model /10/ is used for steady-state analysis of different PIIIN structures with the aim to explain the red-green-blue (RGB) three-color detection mechanism and to gain detailed insight into the operating principle of the PIIIN structures. For the three-terminal structures, the ASPIN simulator was used to optimize the thickness of the individual layers.

The light generation model is based on the particle nature of light and takes into account only the reflection at the front glass surface. The flux of photons is taken to decay exponentially. The absorption coefficient in each layer is wavelength dependent and corresponds to the imaginary part of the complex refractive index. Although the model does not account either for interference or for the numerous reflections in the multi-layer structure, the model gives a good agreement with the experimental results for structures deposited on rough TCO (with haze) /11,12/. For flat TCOs (without haze), an accurate numerical modeling should include the wave nature of light that accounts for light interference effects, especially in the long wavelength range of the visible light spectrum /13,14/.

3. UNIPOLAR BIAS-CONTROLLED COLOR DETECTION PRINCIPLE IN PIIIN DETECTORS

For high short-circuit current in PIN a-Si:H solar cells, the collection efficiency is to be as high as possible throughout the whole visible spectrum. Under reverse bias, the collection efficiency (CE) usually only slightly improves. In a-Si:H color detectors, the CE must be bias controlled. Since PIIIN color detectors operate only under reverse bias, this detection principle is described as unipolar bias-controlled detection principle. By increasing the externally applied reverse bias the CE of PIIIN device can only improve. Thus, to enable different spectral response as a function of reverse bias, the CE at short-circuit conditions must be worse than that one of the PIN solar cell. The electric field plays a key role in governing the CE. To worsen CE of the PIIIN structure at short-circuit conditions, the built-in electric field must be weaker throughout the structure and strongly non-uniform. There are several possibilities:

- to insert appropriate compensational doped layers next to the P and N layer,
- to reduce the doping concentration in the P and N layer,
- to use worse quality I layers with higher defect density.

The thickness of constituent layers with their optical absorption coefficients (α) determine the spatial distribution of the photogeneration of excess carriers. Fig. 1 shows typical generation rate profiles in a P(a-SiC:H)I$_1$(a-SiC:H)I$_2$(a-Si:H)I$_3$(a-SiGe:H)N(a-Si:H) three-color detector. Since the P and I$_1$ layer have a high optical gap (E_{opt}=2.2 eV), the photogeneration region of blue monochromatic illumination (λ=450 nm) dominates in the front part of the PIIIN structure. The abrupt changes of profiles denote interfaces between layers and they are due to higher α in the subsequent layers with the lower optical gap. For red monochromatic illumination (λ=630 nm), the photogeneration region spreads in the last third of the PIIIN structure.

Simulations showed that strong non-uniform electric field profiles in the PIIIN structures always lead to an increased electric field in the front part of the structure, especially at the PI$_1$ interface. Therefore, the PIIIN devices under low reverse bias detect only shorter wavelengths and under higher reverse bias the electric field strengthens throughout the structure, so the whole

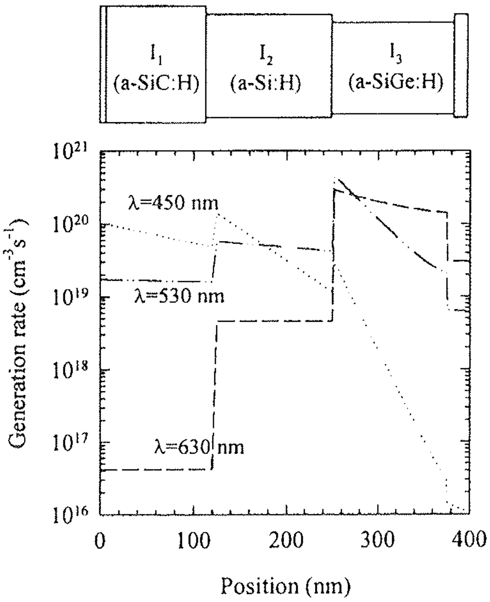


Fig. 1 Generation rate profiles throughout a PI$_1$I$_2$I$_3$N structure for different monochromatic illuminations (1 mW/cm^2).

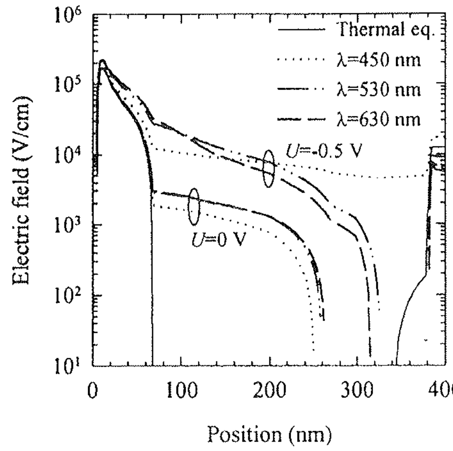


Fig. 2 Calculated electric field profile of the optimized PνI$_1$I$_2$I$_3\pi$N structure for a three-color detector under different monochromatic illuminations and two biases.

range of the visible light spectrum is detected. In case of three-color detector, such a detection principle can generate three signals with the information: blue (B), blue+green (B+G), blue+green+red (B+G+R). The signals are to be transformed into the RGB components. However, the extraction is justified only if the three-color detector behaves as a linear system, i.e. linearly as a function of illumination intensity and insensitively to the bias-light.

4. THREE-COLOR PIIIN DETECTORS

In the study of PI_1I_2N structures /15/, the built-in electric field was profiled using the compensational doping approach in the $P\nu I_1I_2\pi N$ structure or using the high-defect-density I_1* layer approach in the $PI_1{}^*I_2N$ structure. Both analyzed structures suffered the non-linearity and bias-light sensitivity.

In the $PI_1I_2I_3N$ detectors, an a-SiGe:H layer with E_{opt}=1.6 eV is added as the third I layer (I_3) to improve the detection of the long wavelength illumination. The germanium content in a-SiGe:H increases the slope of the tail states and defect density. From /16/, a 5-times higher density of dangling bond states than in the I_2(a-Si:H) layer was selected. The calculated generation rate profiles of the optimized $PI_1I_2I_3N$ structure with 10-100-150-115-25 nm thickness are shown in Fig. 1.

Under short-circuit condition, the electric field should only assist in the collection of excess carriers from short wavelength photons (up to 450 nm). Thus, the built-in electric field should be high only in the front part of the structure, otherwise it should even change its direction. For this purpose, we inserted between the P and I_1 layer a compensational N layer (ν layer) and between the I_3 and N layer a compensational P layer (π layer). The built-in electric field profile of the optimized structure is shown in Fig. 2 (full line). Under short-circuit condition with monochromatic illumination, the electric field changes due to recharging of defects (Fig. 2). Increasing the reverse bias, the electric field recovers first for blue illumination, afterwards for green and finally, also for red illumination. For a good color separation, the doping concentrations in the compensational ν and π layers are to be high or the same effect can be achieved by selecting the P and N layer with lower doping concentration.

Calculated spectral response of the optimized $PI_1I_2I_3N$ structure as a function of reverse bias is presented in Fig. 3. Calculated current-voltage (J-U) characteristics of the optimized $PI_1I_2I_3N$ device for different monochromatic illuminations (1 mW/cm^2) is plotted in Fig. 4. Current-voltage behavior under blue and green illumination is qualitatively similar to the behavior of the PIIN structures. In contrast to the PIIN J-U characteristics under red illumination, a postponed red response with regard to the reverse bias occurred. From the color-separation point of view, this postponed or sometimes even an S-shape behavior is beneficial, since it provides better rejection ratios under lower reverse bias, and different groups /8,9/ experimentally observed it. The origin comes from increased defect states in the I_3 layer, hindering the extraction of excess carries therein due to increased recombination. The extent of increase of the defect states in the I_3 layer increase determines the

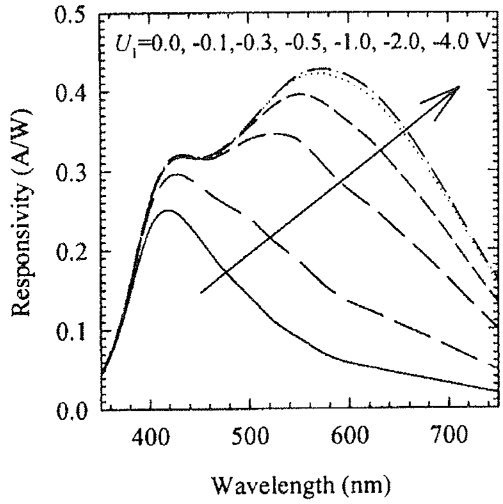


Fig. 3 Calculated spectral response of the optimized $PI_1I_2I_3N$ structure for a three-color detector as a function of reverse bias.

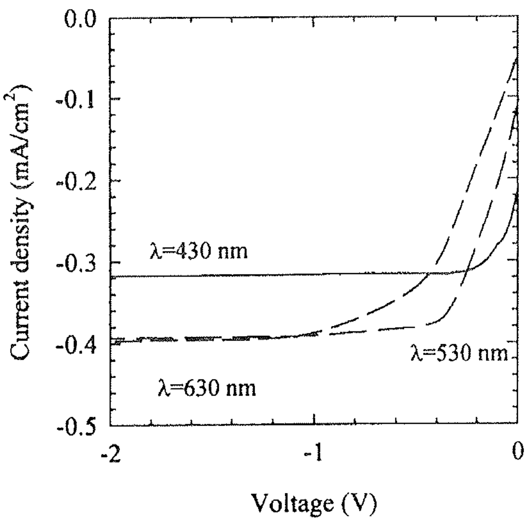


Fig. 4 Calculated J-U characteristics of the optimized $PI_1I_2I_3N$ device for different monochromatic illuminations (1 mW/cm^2).

triggering reverse bias, beyond which the red response steeply starts to increase.

4.1. Examination of bias-light and illumination intensity

For correct extraction of an RGB signal, the PIIIN three-color detectors should exhibit no monochromatic bias-light dependence. We examined the bias-light dependence under the short (450 nm) and long wavelength (650 nm) bias-light. The optimized three-color PIIIN structure, exhibits weak bias-light dependence under short-circuit (detection of B) and under high reverse bias (detection of B+G+R). Unfortunately, strong bias-light dependence occurs in the middle range of reverse bias (Fig. 5). Significant variation of the spectral response is due to the redistribution of the electric field caused by the recharging of defects in the front or the rear part of the device for short wavelength or long wavelength bias-light, respectively. We managed to mitigate the bias-light dependence by reducing the thickness of the device. At the same time, reduced thickness almost proportionally shrinks the reverse bias range of detection, but it affects the spectral response only in the long wavelength region. The results showed that the bias-light dependence correlates with the reverse bias dependence of the long wavelength spectral response (under no bias-light). The higher the variation of red response as a function of reverse bias is, the more bias-light dependent is the device. To reduce the bias-light dependence, we have to sacrifice the suppression of long wavelength response under short-circuit conditions, resulting in a worse color separation. Thus, a trade-off between good color separation and low bias-

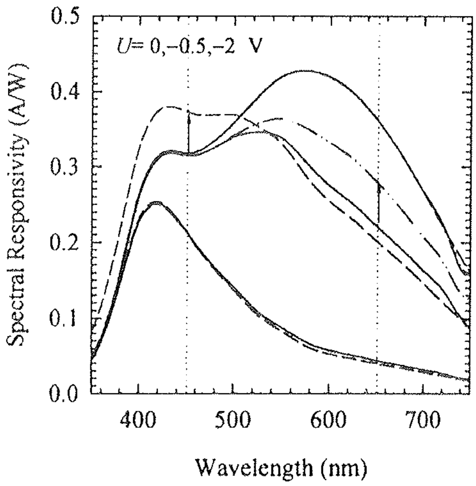


Fig. 5 Calculated spectral responses of the optimized 400 nm thick PIIIN color detector for (0 V, -0.5 V, -2 V) bias without (full line), with 450 nm (dash-dot-dot line) and 650 nm (dashed line) monochromatic bias-light (1 mW/cm^2).

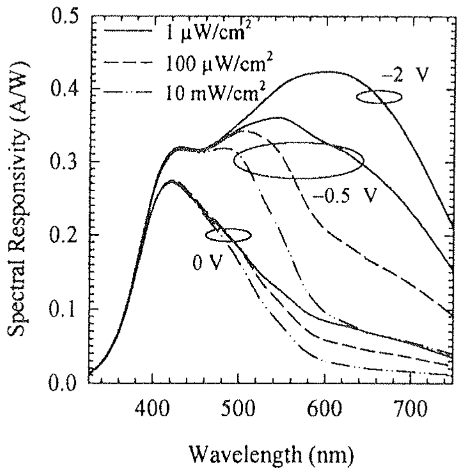


Fig. 6 Calculated spectral responses as a function of illumination intensity (0.001, 0.1, 10 mW/cm^2).

light sensitivity is in the unipolar bias-controlled PIIIN structures unavoidable.

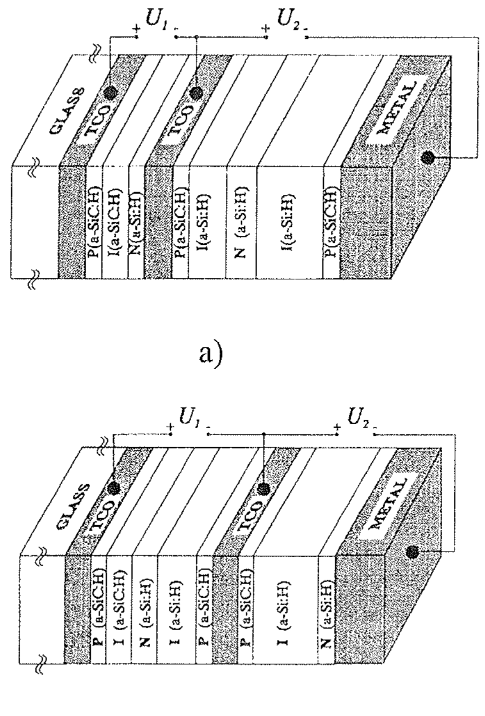
All structures were also examined for different illumination intensities, ranging from μW/cm^2 up to 100 mW/cm^2. Again, larger differences in spectral response arose only in the middle reverse bias range (Fig. 6). Simulations showed that thinner devices exhibit better linearity. Again, a trade-off between good color separation and illumination linearity together with bias-light sensitivity is therefore necessary.

5. BIPOLAR BIAS-CONTROLLED DETECTION PRINCIPLE IN THREE TERMINAL DETECTORS

A family of bipolar bias-controlled three-terminal three-color detectors based on stacked a-Si:H based structures has recently been proposed /17,11,12/. The detectors have the structure $TCO/PI_1N/TCO/PI_2NI_3P$/metal or $TCO/PI_1NI_2P/TCO/PI_3N$/metal. Numerical analysis of both stacked structures, and the optimization of their layer thicknesses for the detection of the fundamental chromatic components - blue, green and red - was performed using the ASPIN numerical simulator /17/.

5.1. Bipolar bias-controlled detection principle

The $TCO/PI_1N/TCO/PI_2NI_3P$/metal structure (Fig. 7a) consists of a top PI_1N diode and two anti-serial diodes in the sequence PI_2NI_3P accompanied by three contacts (TCO_1, TCO_2 and metal). The PI_1N diode independently detects the blue color under reverse bias (U_1 < 0 V), while the PI_2NI_3P structure acts under differ-



b)

Fig. 7 Schematic view of a three-terminal detectors a) $TCO/PI_1N/TCO/PI_2NI_3P$/metal and b) $TCO/PI_1NI_2P/TCO/PI_3N$/metal structure.

ent polarity of the externally applied voltage U_2 as the photodetector for the green or red color. For a negative bias (U_2<0 V), the PI_2N diode operates as a photodetector and the NI_3P diode as an impedance. While most of the high energy photons (blue light) are already absorbed in the top PI_1N diode, the photons of green light generate electron/hole pairs mainly in the PI_2N diode. The red light has the longest penetration depth, and it should be collected in the NI_3P diode under a positive bias (U_2>0 V), under which the PI_2N diode operates as an impedance and the NI_3P as a photodetector. Since both polarities of bias are used, this color detection principle is called bipolar bias-controlled principle.

In the TCO/PI_1NI_2P/TCO/PI_3N/metal structure (Fig. 7b), the PI_3N diode detects the red color independently (U_2<0 V), while the PI_1NI_2P structure acts under application of different bias voltages as a photodetector for the blue and green color (analogous to the operation of PI_2NI_3P discussed above).

The only sophistication is the three-terminal approach that requires some additional technological steps (deposition of TCO_2, interconnections), which have already been successfully utilized for parallel-connected tandem solar cells /18/. With regard to the electronic detection system, this three-terminal approach for the detection of three colors is even more simple than the two-terminal approach.

5.2. Simulation results

Simulations and optimization of the TCO/PI_1N/TCO/PI_2NI_3P/metal and TCO/PI_1NI_2P/TCO/PI_3N/metal structure was performed using the ASPIN numerical device simulator. The optimized thicknesses of the individual layers are listed in Table 1.

For the top I_1-layer and all P-layers, a wide bandgap (a-SiC:H) material is used. The N layer in the PI_1NI_2P structure is thicker in order to provide spectral separation between blue and green color, and hence to have good rejection ratios (>2.0).

The calculated spectral responsivity of the TCO/PI_1NI_2P/TCO/PI_3N/metal structure is plotted in Fig. 8. The structure exhibits narrow spectral responses (full width half magnitude - FWHMs below 150 nm) and high rejection ratios: for the PI_1NI_2P structure both at 430 nm (R_{-1V}/R_{+1V}= 3.0) and at 530 nm (R_{+1V}/R_{-1V}= 5.3). The color suppression is R_{430nm}/R_{530nm}= 5.6 at U_1= -1 V and R_{530nm}/R_{430nm}= 2.8 at U_1= +1 V . For the PI_3N diode, which independently detects red color at reverse applied voltage, the color suppression is also good (R_{630nm}/R_{530nm}= 2.7 at U_2= -1 V).

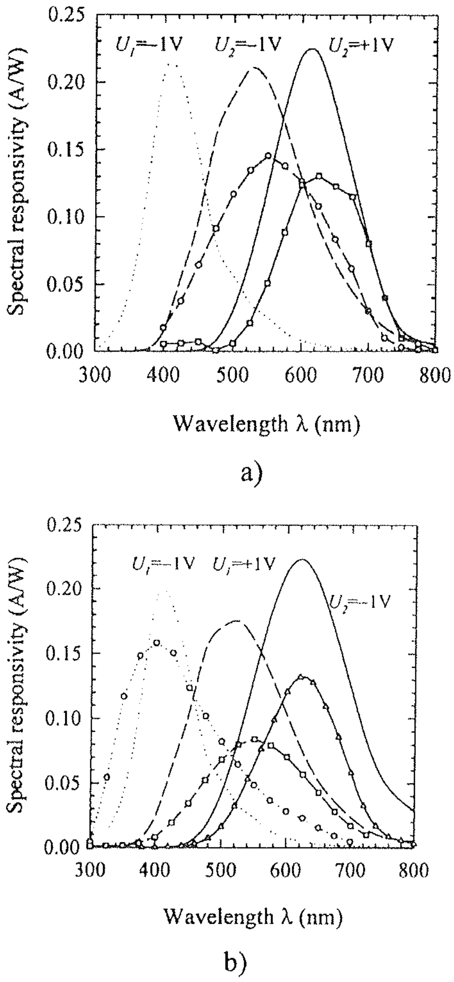


Fig. 8 Calculated (lines) and measured (lines drawn as guides for the eyes with symbols) spectral responsivity of
a) TCO/PI_1N/TCO/PI_2NI_3P/metal and
b) TCO/PI_1NI_2P/TCO/PI_3N/metal structure.

Table 1 Optimised geometrical parameters of three-terminal three-color detectors

	TCO	P	I_1	N	TCO	P	I_2	N	I_3	P
d_S (nm)	1000	5	40	5	1000	11	50	140	369	11
d_E (nm)	740	10	30	10	1000	10	50	130	270	20

	TCO	P	I_1	N	I_2	P	TCO	P	I_3	P
d_S (nm)	1000	5	35	45	60	11	1000	30	365	20
d_E (nm)	1000	10	35	60	60	11	1000	20	365	20

S- simulation; E - experiment

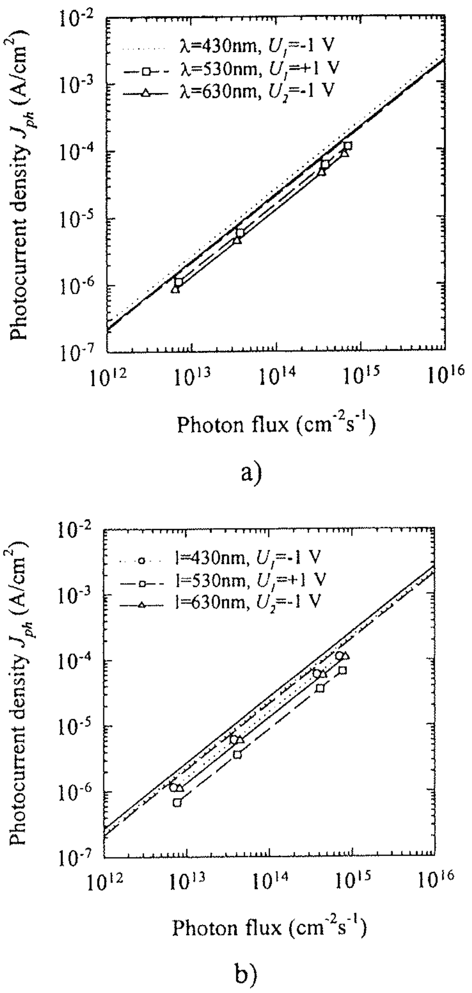


Fig. 9 Calculated (lines) and measured (symbols) photocurrent vs. photon flux under blue (430 nm) and green (530 nm) and red (630 nm) illumination of
a) $TCO/PI_1N/TCO/PI_2NI_3P$/metal and
b) $TCO/PI_1NI_2P/TCO/PI_3N$/metal structure.

Simulations showed that both structures had a linear photocurrent/generation-rate relationship for all three colors at peak wavelengths 450, 530, 635 nm, applying a bias of ±1 V or more (Fig. 9). This linearity allows all three colors to be easily detected with adequate rejection ratios.

5.3. Experimental results

A conventional two-chamber PECVD deposition system (30 x 30 cm^2) was used for the deposition of PIN and PINIP structures. A smooth glass/indium tin oxide substrate was used for the front TCO, and sputtered ZnO for the second TCO. Patterning steps were made by laser scribing /18/.

We started the experimental investigation with the $TCO/PI_1N/TCO/PI_2NI_3P$/metal structure. It had already been demonstrated /11/ that the PI_2NI_3P structure exhibits very good (>3.0) rejection ratios and color suppressions between green and red color (Fig. 8a, lines with symbols). However, the thickness of the top PI_1N diode (10-30-10 nm) was too small to prevent the shunt defects, thus hindering the detection of the blue color. We managed to reduce the top PI_1N diode thickness (while preserving its functionality) to 90 nm. But, the spectral response is too broad (FWHM=210 nm) and the maximum is located at 455 nm. Despite the I_1 layer thickness reduction, the spectral responsivity of PI_1N diode decreases very slowly in the wavelength region above 500 nm, indicating that an a-SiC:H material with a higher optical gap should be preferred.

The problem of the top PI_1N diode functionality was solved with the $TCO/PI_1NI_2P/TCO/PI_3N$/metal stacked structure. Since the whole PI_1NI_2P (10-35-60-60-15 nm) structure was around 180 nm thick, local defects impeding the photodetection function were eliminated. The fabricated PI_1NI_2P structure shows good detection of blue and green color (Fig. 8b; lines with symbols). It exhibits narrow spectral responses ($FWHM_{(U1=-1V)}$=165nm and $FWHM_{(U1=+1V)}$=180 nm) and high rejection ratios, at λ=450 nm with R_{-1V}/R_{+1V}= 7.8 and at λ=530 nm with R_{+1V}/R_{-1V}= 1.3. The measured color suppression is high, R_{450nm}/R_{530nm}= 4.1 at U_1= -1 V and R_{530nm}/R_{450nm}= 2.3 at U_1= +1 V, and the dynamic range is also very high.

The fabricated bottom PI_3N (20-365-20 nm) diode detects independently the red color under reverse bias. Its measured spectral responsivity at U_2= -1 V is plotted in Fig. 8b (lines with triangles). It has the narrowest FWHM (140 nm) in the structure and a high color suppression (R_{630nm}/R_{530nm}= 3.1 at U_2= -1 V).

The linear photocurrent/generation-rate dependence of both three-terminal structures derived from the simulations was confirmed by measurements under different monochromatic illumination intensities ranging from 10^{12} to 10^{15} photons per cm^2s (Fig. 9; lines with symbols).

Comparison between simulated and measured results in Fig. 8 reveals the following: a) losses in the glass and front TCO were higher than assumed; b) the I_1 layer absorbs too large a part of the long-wavelength light; c) the second TCO acts as a good reflector, resulting in a large difference between simulated and measured results for the PI_3N diode.

Thickness optimization of the second TCO will be necessary. Good reflectivity of the second TCO and thus low responsivity of the PI_3N diode could be partly mitigated with an improved reflection at the back contact.

6. CONCLUSIONS

We used numerical modeling as a tool for analysis of thin film color detectors based on a-Si:H.

The device physics of two-terminal a-Si:H based three-color detectors with the multi-layer multi-bandgap PIIIN structure was investigated. They operate under different reverse (unipolar) biases. The PIIIN structures suffer from high bias-light sensitivity and non-linearity of the illumination intensity, although this sensitivity can be mitigated with the higher built-in electric field at the expense of worse color separation. The optimized PIIIN structure operates under lower range of reverse bias and the I_3 layer with an increased defect density results in a postponed red response. The results lead to the conclusion that for a more linear and bias-light independent color detection in the PIIN devices, we have to sacrifice the quality of three color separation or vice versa.

The three-terminal structures operate under forward and reverse (bipolar) biases. They exhibit excellent linearity, a high dynamic range and they directly generate a RGB-signal.

Due to stringent thickness conditions (<60 nm) for the top PI_1N diode in the $TCO/PI_1N/TCO/PI_2NI_3P$/metal structure, and additionally due to high reflection of the second TCO, the steady-state experimental results indicate that the $TCO/PI_1NI_2P/TCO/PI_3N$/metal structure gained an advantage over the $TCO/PI_1N/TCO/PI_2NI_3P$/metal structure.

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