UDK621.3:(53+54+621+66), ISSN0352-9045 Informacije MIDEM 31(2001)4, Ljubljana

COLOR ALIASING FREE DETECTORS

H. Stiebig, D. Knipp, H. Wagner

Forschungszentrum Jülich, Institute of Photovoltaic, Jülich, Germany

INVITED PAPER
MIDEM 2001 CONFERENCE
10.10.01 - 12.10.01, Hotel Zlatorog, Bohinj

Key words: semiconductors, microelectronics, image processing, colour images, CFA, Color Filter Array, color imagers, recording cameras, CMOS colour cameras, CCD colour cameras, colour aliasing free detectors, MOIRE effect, aliasing effect, colour separation, colour sensors, colour recognition

Abstract: Color images are commonly captured with sensor arrays covered with a mosaic of rgb-filters. Hence one-chip color imagers (CMOS and CCD color cameras) suffer from color aliasing or color moiré effects. In order to overcome these limitations color sensors based on vertically integrated diodes were realized. The complete color information of the color aliasing free sensor can be detected at the same spatial position without using additional optical filters. The color separation is realized by the wavelength dependent absorption of the incorporated material in the depth of the devices. A promising material for sensor application in the visible range is amorphous silicon and its alloys. Thin film systems based on amorphous two terminal and stacked multi terminal devices are fabricated by a low temperature CVD process. The spectral sensitivity of the sensors can be controlled by the optical and optoelectronic properties of the materials on one hand and the design of the devices on the other hand. The operation principle of the sensors will be presented and the different detection concepts will be compared regarding their application in the field of color recognition and digital imaging.

Detektorji barvne svetlobe brez motenj

Ključne besede: polprevodniki, mikroelektronika, procesiranje slik, slike barvne, CFA polje filtrov barvnih, upodabljalniki slik, kamere snemalne, CMOS kamere barvne, CCD kamere barvne, detektorji barv brez motenj, MOIRE efekt, ločevanje barv, senzorji barv, razpoznavanje barv

Izvleček: Barvne slike ponavadi zajemamo s senzorskimi polji, ki so pokrita z mozaikom RGB filtrov. Zaradi barvnega moire efekta prihaja do popačenj pri zajemu slik (CMOS in CCD barvne kamere). Izdelali smo barvne senzorje z vertikalno integriranimi diodami ravno z namenom izogniti se temu problemu. Popolno barvno informacijo brez popačenja lahko zajamemo na isti prostorski lokaciji brez uporabe dodatnih optičnih filtrov. Ločitev barv izvedemo z izbiro materialov, ki omogočajo absorpcijo v odvisnosti od valovne dolžine v različnih globinah detektorja. Obetajoči material za tovrsten senzor v vidnem področju so amorfni silicij in njegove zlitine. Z nizkotemperaturnim CVD nanašanjem smo izdelali tankoplastne strukture komponent z dvema izvodoma in večplastne strukture z večimi izvodi. Spektralno občutljivost senzorjev lahko na eni strani kontroliramo z optičnimi in optoelektronskimi lastnostmi uporabljenih materialov, na drugi pa z načrtovanjem komponente. V prispevku predstavimo princip delovanje takih senzorjev ter primerjamo različne koncepte detekcije glede na uporabo na področju zaznave barv in digitalnega upodabljanja.

1. Introduction

Color image processing is usually performed with the aid of CFA (color filter array) coated CCD or CMOS sensor arrays. However, color detection with a CFA leads to the color moiré or color aliasing effect, which is observed when structures with high spatial frequencies are captured. Furthermore, traditional sensor systems exhibit a rather limited resolution and low area fill factor, because one color pixel is split into several chromatic sub pixels. In order to overcome the color moiré effect, vertically integrated sensor structures have been proposed, which detect the color information in the depth of the sensor structure. Various sensor structures have been realized by using different materials, design concepts and contact configurations /1-12/. Nevertheless, the detection mechanism of all vertically integrated sensors can be basically described by a related operation principle. Due to the wavelength dependent absorption of the semiconductor material, photons are absorbed at various depths in the material so that the color information can be detected in the depth of the device.

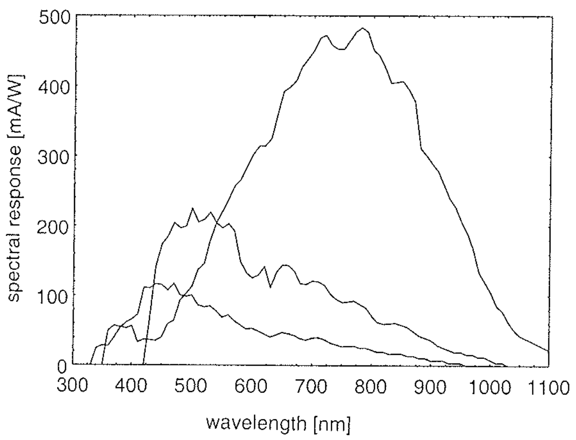

Fig. 1: Spectral sensitivity of three stacked crystalline p/n-junctions /1/.

Vertically integrated sensors based on CMOS/CCD processes were presented e.g. by Seitz et al. /1/ and Poenar et al. /2/. As example, the system of Seitz et al. consists of three vertically integrated pn-junctions fabricated by a BiCMOS process. The spectral response of the detector system is shown in Fig. 1. The color separation is limited by the fixed optical band gap of the crystalline silicon material. To overcome this limitation and to improve the spectral sensitivity the optical band gap of the individual absorption regions has to be varied. Thus, thin film devices based on amorphous silicon (a-Si:H) and its alloys are favorable. Amorphous silicon alloys exhibit a high photosensitivity from the UVA (ultra violet A) to the near IR (infra red) part of the spectrum /13, 14/. In order to match the demand of different applications the optical band gap as well as the transport properties of the material can be controlled over a wide range by the deposition conditions. Additionally, a-Si:H multi-layer structures can be deposited on top of an amorphous, polycrystalline or crystalline active matrix array leading to significantly enhanced area fill factors of pixel-addressed sensors /15, 16/.

Several amorphous thin film detector concepts were proposed to separate the color information of the visible spectrum. The structures consist of pin-diodes with modified absorption layers /3-5/, pinip- or nipin-structures /6-8/ and more complex layer sequences /9-12/. a-Si:H thin film color sensors can be separated in two different classes. Sensors of the first class allow the separation of the color information by two terminal devices /3-9/. The color separation is realized by a shift of the collection region of the photo-generated carriers within the device due to the variation of the applied voltages. Two terminal devices are characterized by a simple structure but the sequential readout process limits the application of these devices. The second class contains color sensors based on vertically stacked diodes /10/. These sensors enable the advantage of a parallel detection of the chromatic color information at the same position, but require at least 4 interconnections between the sensor and the processing electronics. Additionally, a few combinations of these two classes (stacked diodes and detectors with a voltage controlled sensitivity) were also realized /11, 12/ resulting in devices with 3 and more terminals. In this paper different thin film sensors based on the two different sensor classes will be compared. The results of the developed structures will be presented and the advantages and disadvantages of the structure will be discussed.

2. Experiment

The samples have been deposited in a multi-chamber PECVD (plasma enhanced chemical vapor deposition) system at 210°C on glass substrates coated with flat TCO (transparent conductive oxide). The TCO layer has been realized by rf-magnetron sputtered ZnO /17/. In the case of stacked diodes, two additional TCO layers have been introduced to contact the individual diodes and to act as an etching stop during the patterning process. All detectors were patterned using photolithography and reactive ion etching. In the case of four terminal devices a simple 3-mask process was applied. For all samples, we use thermally evaporated aluminum as a back contact and the area of the test pixels ranges from 3 to 10 mm^2. In order to vary the optical band gap within the devices the amorphous silicon was alloyed with carbon or germanium using gas mixtures of silane and methane or mixtures of silane and germane, respectively. The optical band gaps of the i-layers increase with enhanced carbon content and decrease by alloying germanium. P- and n-type doped layers were realized by adding trimethylboron and phosphine, respectively. A detailed description of the deposition parameters is given elsewhere /14, 18/. The optical band gap of the a-Si:H layers was deduced from optical reflection and transmission measurements using separately prepared samples.

3. Results

3.1 Color detector based on a two terminal nipiin structure

Nipiin structures basically consist of two anti serial connected diodes. Applying different bipolar voltages generates the three color signals. The spectral response of a nipiin three color detector with modified band gaps and different $\mu\tau$-(mobility lifetime)-products in the i-layers of the top and bottom diode is shown in Fig. 2. The maximum of

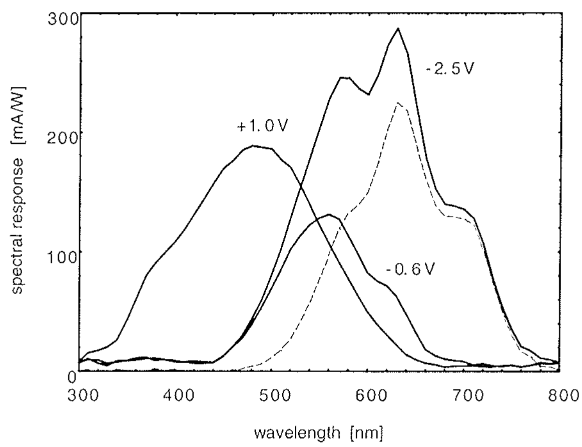

Fig. 2: *Measured spectral response of a nipiin three-color sensor at applied voltages of V = 1.0V, -0.6V and –2.5V (solid line) and the calculated difference between the sensitivity at V = -2.5V and V = -0.6V (dashed line).*

the voltage controlled spectral response of the sensor shifts in the bias range between V = -2.5V and V= 1.0V from red to green and blue. The spatial distribution of the band gap and the $\mu\tau$-product is given schematically in Fig. 3. A silicon carbon layer with an optical band gap of 2.0 eV and a thickness of 125nm defines the absorption region i^{I} in the top diode. The layer i^{II} is deposited by amorphous silicon. The optical band gap and the thickness, d_i, is 1.75 eV and 200nm, respectively. In order to get a high absorption for photons with low energy, region i^{III} was fabricated by a silicon germanium layer with an optical band gap of 1.65 eV.

The behavior of the color sensor can be explained as follows: The application of different voltages causes distinct band bending and changes the preferential collection region of the photo-generated carriers within the absorption regions of the device. For positive applied voltages the generated carriers in the reverse biased top diode are collected, while the photo generated carriers in the forward biased bottom diode recombine. Thus the photocurrent of the device is determined by the absorption within the top diode. The spectral response of the device exhibits blue sensitivity with a maximum at 480nm as a result of the high absorption coefficient of a-SiC:H for light with shorter wavelengths and low absorption for light with longer wavelength. An increase of the positive voltage enhances the spectral response only slightly, because wide band gap material with low defect density was employed in the top diode. Hence, in this region nearly all photo-generated carriers are extracted at low reverse bias (Fig. 2). At negative voltages the photocurrent is determined by the electrons and holes generated and collected in the bottom diode, whereas the photo-generated carriers in the top diode recombine.

To achieve a high linearity and linearly independent spectral response curves the band gap of the absorption layers must decrease from the front contact to the back contact, whereas the $\mu\tau$-product of the layers in the bottom diode increases from the n-layers to the p-layer (Fig. 3). For the

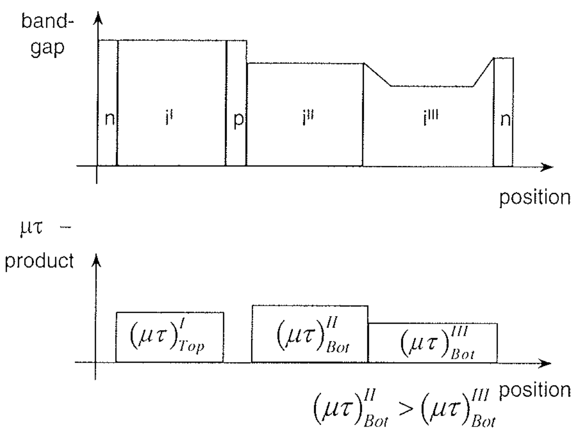

Fig. 3: *Band gap and $\mu\tau$-product of a nipiin three-color sensor.*

green/red separation at low negative voltages an a-SiGe:H-layer is introduced in the rear part of the absorption layer in the bottom diode, since a small amount of germanium alloyed to amorphous silicon increases the defect density and reduces the ambipolar diffusion length in the a-SiGe:H material /18/. Thus, the i-layer of the bottom diode consists of two regions with different $\mu\tau$-products. At low negative bias (-0.6 V) mainly the carriers generated in i^{II}-layer are extracted, while the carriers in the rear part of the bottom diode (i^{III}-layer) recombine. Thus, the device is sensitive to green light and the spectral sensitivity exhibits a maximum at 560nm. The recombination of carriers in the rear part is caused by the low $\mu\tau$-product combined with the low electric field within the i^{III}-layer. All carriers in the bottom diode are collected at high negative bias and the device yields a maximum of the spectral response for red illumination (630nm) at V = -2.5V. The spikes of the spectral response for longer wavelength, especially, at V = -2.5V can be attributed to interference effects within the whole layer stack. In this case the product of the absorption coefficient of the material and the layer thickness is smaller than the penetration depth of the photons for longer wavelengths.

At higher negative voltages the measured signal is determined by green and the red light. In order to separate the red signal from the measured signal at higher negative bias, the green response detected at low negative bias has to be subtracted. The dashed line in Fig. 2 indicates the difference between the two curves and demonstrates the good color separation of a nipiin color sensor. For accurate color recognition the measured spectral sensitivities can be converted into a standard color space (e.g. CIE) /19/. However, the subtraction and the transformation of the sensitivities into a standard color space assume that the spectral response curves are linear independent. For this device design three linear independent spectral response curves were achieved /20/.

Besides the separation of linear independent curves of the spectral response, a high dynamic and a good linearity are necessary to apply a detector for image processing. Since no saturation of the photocurrent is observed for realistic illumination conditions (< 10000 lx) the dynamic range of the device is defined as the ratio between the photocurrent under 1000 lx white light illumination and the dark current. A high dynamic can only be realized by using low color sensitive voltages, in order to avoid a distinct increase of the dark current /7/. The nipiin three-color detector optimized for low voltage color sensing exhibits a dynamic range exceeding 90 dB in the active color detection range from -2.5V to +1.0V (Fig. 4). The dark current increases

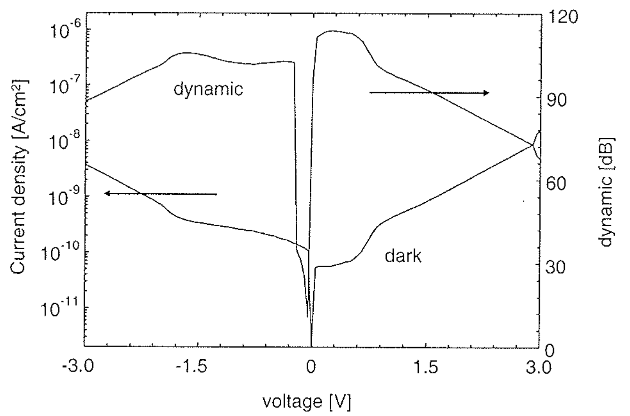

Fig. 4: *Dynamic and dark current of a three-color nipiin sensor.*

for higher voltages thereby limiting the dynamic performance of the color detector. Numerical modeling of the dark

I/V-curves reveals that for higher positive bias (V > 1.0V) the p-layer is flooded with electrons caused by the thin top diode. More insight into the transport and recombination model is given elsewhere /7/. The examination of the photocurrent as a function of the incident photon flux reveals that the nipiin sensor is highly linear over a wide range of intensity. The photocurrent can be described by a power law expression with an exponent close to one (0.95-0.98).

The delay time of the transient photocurrent after voltage switching is a further criterion of the detector performance, since a red/green/blue (RGB) signal can be generated sequentially after switching the applied voltages. The curves in Fig. 5 show the maximum frame rate for an optimized G-R-B-switching sequence as a function of the photon flux. The frame rate describes the reciprocal value of the sum of the photocurrent delay times t_d after switching from +1.0V to -0.6V, -0.6V to -2.5V and from -2.5V to +1.0V and an integration time of 1.5 ms of the signal (0.5 ms per color) using an additional read out electronic. A nearly linear relationship between the frame rate and the photon flux (ϕ) is observed for $\phi > 3*10^{11} cm^{-2}s^{-1}$, whereas a wavelength dependent hyper linear correlation is detected for lower ϕ. This hyper linear behavior is caused by the influence of the dark current and the recharging behavior in the dark, which is dominated for such low levels of intensity (moon light). A nearly linear correlation is found for high ϕ, since the integration time is much smaller than the total delay time of the sensor. Thus, color recognition is possible for frame rates above or equal to the curves in Fig. 5. For frame rates below the curves a color lag has to be considered, since the sum of the delay times and integration times is greater than the minimal requisite time to reach the steady state photocurrent.

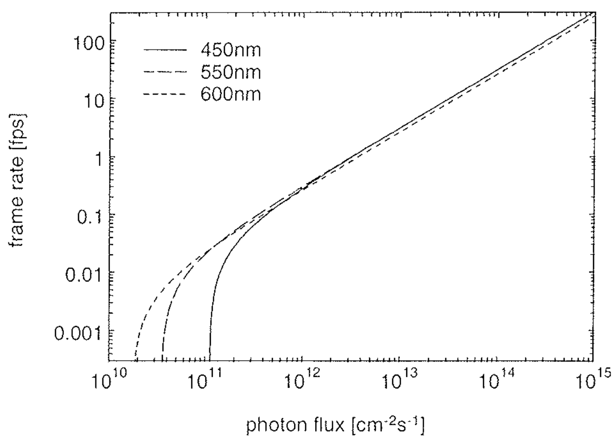

Fig. 5: Frame rate for an optimized RGB-switching sequence as a function of the photon flux for different wavelengths.

The strong illumination dependence of the transient response complicates the application of detector systems based on two anti serial connected diodes (as nipin or pinip-detectors) for color detection. Particularly, for low levels of illumination a deconvolution of the signal is necessary. A detailed analysis of the transient phenomena are discussed in detail elsewhere /21, 22/.

A 2-color detector array with 256x256 pixels was successfully demonstrated by Mulato and coworkers /23/, which combines pinip-structures with TFT read-out electronics. However, based on the previous discussed transient behavior real time imaging is restricted. In order to overcome these limitations, unipolar sensors based on a pin diode with modified absorption regions have been developed. Additionally, due to operating voltages of only one polarity, the structure is further on compatible to standard CMOS circuits.

3.2 Color detector based on a two terminal unipolar piiin structure

In Fig. 6 the schematic band diagram (a) and $\mu\tau$-product (b) of a piiin structure is shown. The optical band gap and

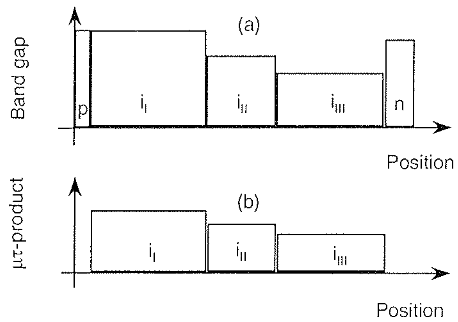

Fig. 6: Schematically spatial distribution of the band gap (a) and the $\mu\tau$-product (b) of a piiin structure.

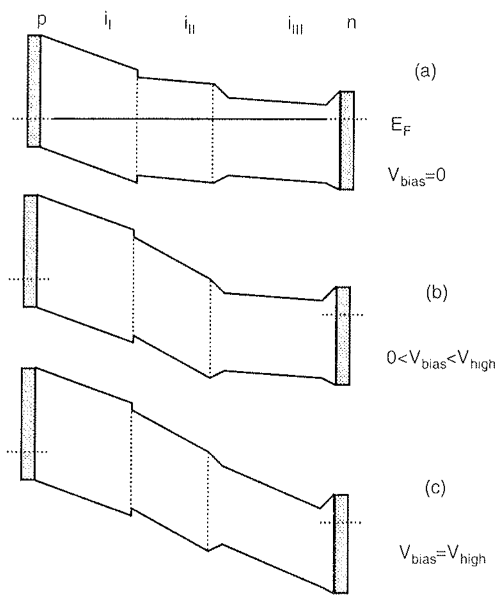

Fig. 7: Schematically band scheme of a pin structure according to Fig. 6 for short circuit (a), inter mediate reverse bias (b) and high reverse bias (c) conditions.

$\mu\tau$-product of the absorption layer decreases from the p- to the n-layer, to facilitate color separation. An amorphous silicon carbon layer with an optical band gap of 2.0eV and a thickness of 110nm was incorporated as absorption layer i^{I}. In region II material with an optical band gap of 1.8 eV and a thickness of 90nm is employed. For red light detection in the rear part (region III) an a-SiGe:H layer is introduced with an optical band gap of 1.65eV.

The schematic band structures for different applied voltages are shown in Fig. 7 to describe the electronic transport and the extraction of photo-generated carriers. Under short circuit conditions a strong band bending is observed only in the front part of the absorption layer (Fig. 7a). Thus, only the photo generated carriers in region I can be extracted, whereas the electric field in region II and III is not high enough to collect the photo-generated electrons and holes. In the case of intermediate reverse voltage the electric field in region II is enhanced and in addition to the extracted carriers from region I the carriers in region II are collected and contribute to the over-all photocurrent. The generated carriers in region III still recombine. In the case of a high reverse voltage applied to the piiin structure the electric field is high enough to extract nearly all photo-generated carriers. The spectral sensitivity of a piiin structure (solid lines) is shown in Fig. 8. The sensor exhibits a maximum of

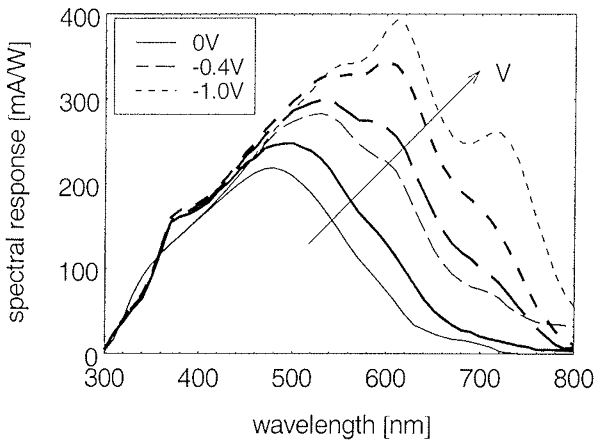

Fig. 8: Measured spectral response (bold lines) at 0V, -0.4V, -1.0V applied voltages and optically simulated data (thin lines) of a piiin diode.

the spectral response at 500nm measured under short circuit conditions. An increase of the reverse bias up to -0.4V leads to the extraction of photo-generated carriers out of region I and II and the maximum of the sensitivity shifts to 540nm. At high reverse bias (V = -1.0V) nearly all photo-generated carriers were extracted out of the whole i-layer. Consequently, the spectral response shifts to longer wavelengths detecting a maximum at 600nm.

To gain deeper insides into the behavior of the sensors we modeled the optical behavior of such a complex detector system, because all layers of the layer stack have an influence on the device characteristic. The program uses the complex refractive indices of each layer as input parameter. The calculated optical generation profiles have shown that mainly blue light is absorbed in region I, whereas green light is mainly absorbed in region I and II and red light in region III /4/. In order to compare the simulations with the measured spectral response data, we integrated the generation profiles in the three regions of the absorption layer. Neglecting the electronic losses (recombination) the spectral response determines the lower and the upper limit of the sensitivity. Under short circuit conditions the measured spectral response is higher than the simulated curve, which considers only the photo-generated carriers of region I. The higher photocurrent can be attributed to the extraction of generated carriers out of region II and III. At high reverse voltage the experimentally determined spectral response is smaller than the simulated curve. This difference can be explained by recombination losses of carriers especially generated in region III. The result indicates, that for blue and green illumination carriers generated in the middle and rear part of the structure contribute to the photocurrent. Since the collection efficiency of these carriers depends strongly on the applied voltages, the linearity of the device is resticted /4, 24, 25/. Especially, the linear independent spectral response curves at intermediate voltages complicate or prevent an accurate color acquisition /4/. However, linear independent curves can only be guaranteed by the application of one sensor for each individual chromatic signal.

3.3 Color sensors based on vertically stacked p-i-i-n diodes

3-channel sensors based on three vertically stacked pin diodes allow the simultaneous detection and read-out of the sensor signals. Furthermore, the spectral response curves are linear independent. A pre-processing electronic can perform the read-out process, which latches, processes and transfers the signals to a color-processing unit. In opposite to nipiin or piiin structures discussed above the photo-generated carriers can be stored within the diode and no additional pixel capacity is needed. This possibility reduces the required area for the pixel electronic and simplifies the shrinking of the pixel pitch. The multilayer system consists of three vertically integrated diodes (Fig. 9). After the deposition of the complete layer stack

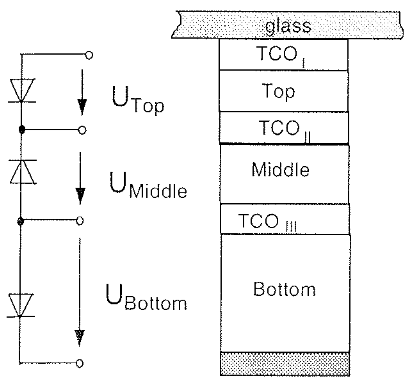

Fig. 9: Schematic configuration of a 3-channel sensor based on three vertically stacked diodes.

the diodes were patterned by a 3-mask process to contact the individual terminals. The sensor has been illuminated through the glass substrate. The spectral response curves of the 3-color detector (Fig. 10), measured under short circuit conditions, exhibit a maximum at 410nm, 535nm

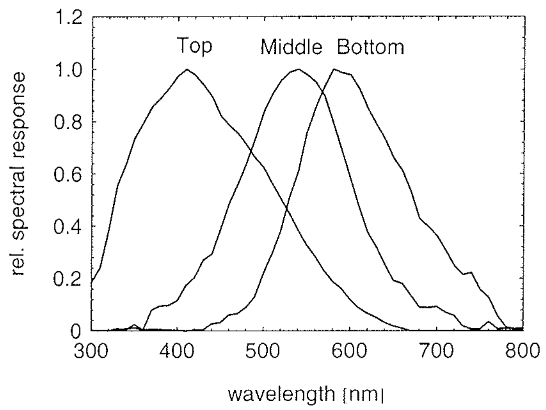

Fig. 10: Measured spectral response of a 3-channel sensor based on three vertically integrated pin diodes. The sensitivity is measured under short circuit conditions.

and 590nm and a Full Width at Half Maximum (FWHM) of 195nm, 147nm and 144nm, respectively. The preferential absorption of blue, green and red light is detected in the top, middle and bottom diode, respectively, by adjusting band gap and thickness of the absorption layers. The optical band gap of the absorption layers in the top, middle and bottom diode is 2.2 eV, 1.9 eV and 1.75 eV, respectively, by alloying carbon to the deposition gas silane. The amplitudes of the spectral response curves differ by less than a factor of 3. However, the color separation of green light in the different diodes is only moderate. The photocurrent of the top diode of the 3-channel detector under blue (λ = 450nm) and green (λ = 550nm) illumination differs only by a factor of around 2.5. In comparison, a CCD camera coated with optical filters has a separation ratio of more than 40 between blue (450nm) and green light (550nm) /26/. This effect is caused by the lack of optoelectronic materials with a high optical band gap and good electronic properties. A detailed analysis of the optical properties and colorimetric characterization of the sensor is given elsewhere /27/.

The dynamic range for all three diodes exceeds 80 dB in the bias voltage range from 0V down to -0.5V. For the middle and bottom diode, the dynamic is above 90 dB; since the dark current is lower than 2×10^{-10} A/cm^2 under reverse bias voltage of -0.5V.

3.4 Stacked color sensors comprising detectors with a voltage controlled sensitivity

One of the simplest ways to generate linear independent spectral response curves and to minimize the interconnections between the detector and the electronic based on the combination of a pinip or nipin system with a pin diode /11/. A different attempt is shown in Fig. 11. The sensor system consists of three stacked pinip diodes. A preprocessing electronic can perform the read-out process, which latches, processes and transfers the signals to a color-processing unit (Fig. 11). A reduction of the mismatch

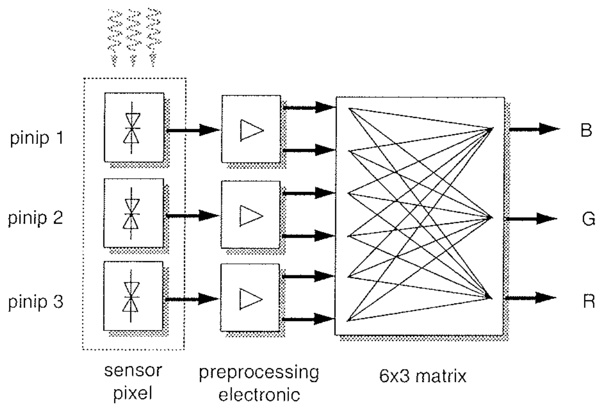

Fig. 11: Schematic configuration of a 6-channel sensor in combination with a preprocessing electronic and color processing unit.

between the spectral sensitivity of the color detector and the human eye can be achieved by the generation of more than three linearly independent spectral response curves. Thus, we have realized a 6-channel sensor, which can be read-out by two shots.

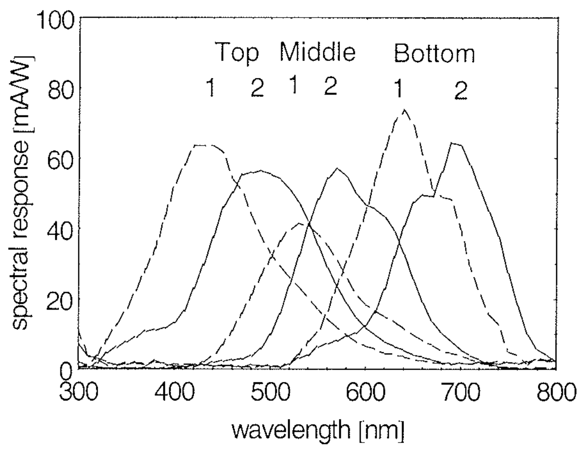

Fig. 12: Measured spectral response of 6-channel sensor. Curves 2 are measured applying 1.0V (solid lines) and curves 1 are measured applying -1.0V (dashed lines) bias voltages on the pinip-diodes of the different terminals.

Pinip structures show an operation principle similar to nipiin structures. At negative applied bias voltages, the top diode is reverse biased, whereas the back diode is forward biased. The photocurrent is determined by the reverse biased front pin diode. Changing the applied voltage from -1.0V to +1.0V shifts the preferential collection region of the generated electron/hole pairs from the front to the bottom part of the individual pinip structures. The spectral response of the rear diode shifts to longer wavelengths, because the first part of the pinip structure acts as an optical filter. After transferring the sensor signal from the detector to the pre-processing electronic the signal is latched and the applied bias voltage is changed. Depending on the pre-processing electronic, the sensor signal can be either transferred sequentially or parallel to the color-processing unit. Afterwards a 6x3 matrix transforms the sensor signals into a standard color space like CIEXYZ. Fig. 12 shows the measured spectral sensitivity of the 4-terminal device with maxima at 430nm, 490nm, 530nm, 570nm, 640nm and 690nm. The spectral response curves with FWHM of 128nm, 133nm, 111nm, 120nm, 113nm and 116nm, respectively, can be taken by two shots, without using optical filters. A very good adjustment of the optical absorption for this device structures is achieved because the maxima of the spectral response vary by less than a factor of 1.8. The dynamic of the three pinip-structures exceeds 75dB in the bias range of +1.0V/-1.0V.

4. Discussion

In the following we discuss the different sensor concepts. We will focus only on voltage-controlled two terminal detectors and detectors based on three stacked p-i-n-diodes. The 6-channel sensor will not be discussed here, because the device combines the advantages and disadvantages of voltage-controlled two terminal and multi-terminal devices. The performance of the sensors is summarized in Tab. 1. The nipiin and piiin structures are specified by a simple contact configuration and a sequential read-out process, whereas the stacked sensors are stated by a more complex contact configuration. But in the latter case all channels can be read out at the same time. As a consequence of the different contact configurations, an additional pixel capacitor is required to store the photo-generated charge of the nipiin and piiin structures.

Device	nipiin	piiin	stacked p-i-n diodes
Color separation	moderate	moderate	good
Terminals	2	2	4
Dynamic	80-90dB	80-90dB	80-90dB
Linearity	good	good	very good
Processing	≥ 1 mask	≥ 1 mask	≥ 3 masks
Read out	External capacitor	External capacitor	Charge storage mode
Application	Color recognition	Color recognition	Digital Photography

Tab.1: *Comparison of the device performance of thin film color sensors.*

All presented sensors exhibit a dynamic range exceeding 4 orders of magnitude. The photosensitivity of the sensors deviates only by a factor of 2, so that the dark current of the devices mainly determines the dynamic. For the two terminal devices the material with the highest defect density primarily determines the dark current, which is typically employed in the rear part of the sensor. Furthermore, the dark current of the nipiin structure for higher voltages is influenced by the flooding of the central p-layer with electrons /7, 22/. In contrast to the limitation of the bottom diode of the nipiin structure, the dynamic of the stacked sensor is limited by the properties of the top diode. Due to the thin absorption layer of the top diode the current is influenced by micro shunts. Although the device design differs significantly, similar dark currents are measured for two terminal and stacked diode sensors. Therefore, the application of amorphous silicon based sensor is only limited for very low levels of intensity. A common feature of two terminal device structures is the distinct transient behavior, which limits real time imaging. A further aspect, which is of interest to compare different sensors, is the color separation. The spectral response curves of the piiin detector are very broad, which leads to noise problems when the RGB-signal is detected. Additionally, the spectral sensitivities depend on the illumination conditions. The linear independence of the color separation of the piiin sensor is significantly reduced in comparison to a nipiin and a stacked sensor structure. Especially, for intermediate bias voltages (green sensitivity) the sensor exhibits a linear dependence of the spectral sensitivity, which will hinder accurate color recognition.

In general, all color sensors or color sensor arrays (with and without optical filters) exhibit restrictions if the performance is compared with human vision. The mismatch between the human perception of color and the performance of technical sensors leads to metameric errors. Hence, the color space of the detector and the color space of the human eye represented by the colorimetric standard observer (CIE 1931) have to be matched /19/.

In contrast to sensors with color filters, which facilitates a reduction of the color error by the individual tuning of the filters for red, green and blue, the absorption within the individual i-layers of the presented color aliasing free sensors can not be independently optimized, because the sensor channels or absorption regions are vertically integrated. Hence, the color separation of the two terminal devices exhibit a moderate and the stacked color sensor a good color separation. Due to the detection of more than one color within one diode of the two terminal devices a special design of the diodes is required. As a result of these constraints the color separation of the sensors is limited by the optical and the transport properties of the material. Only certain materials fulfill the requirement to be employed in two terminal color sensors. The color sensors based on vertically integrated diodes are more or less only limited by the optical properties of the material. Thus, the device designer has higher flexibility in adapting the color separation to the required application in comparison to the two terminal devices. However, the spectral sensitivity of the top diode of the 3-channel sensor is mainly determined by the absorption within this diode. The spectral response of the middle and bottom diode is also influenced by the transmission properties of the layers arranged in direction of the incident light. For example: the sensitivity of the green and the red channel is determined by the design of the individual diodes and the absorption/transmission of the diode for blue and blue/green, respectively. As a consequence an individual modification of one sensor channel is only possible to a certain scope. In spite of this drawback, the color error of the stacked sensor system has been reduced to the level of commercial sensor arrays with optical filters /27/.

We have shown that nipiin and piiin structures are very good candidates for low cost applications, which require a moderate color separation and no real time imaging. The concept of vertically integrated pin diodes is more complex but the high flexibility in tuning the spectral sensitivity exhibits potential for high-end applications like multi spectral technology, digital photography or document archiving.

5. Conclusion

Novel amorphous silicon multi-spectral color detectors based on two terminal devices and stacked thin film structures have been developed and the optoelectronic properties of these devices have been discussed and compared. The thin film structures enable color aliasing free color detection. Accordingly, the complete color information can be detected at the same position without the aid of optical filters. The color separation is realized by the wavelength dependent absorption in the depth of the material. In order to match the demands of different applications the optical as well as the electronic properties of the individual regions of the device can be optimized due to the flexibility of the PECVD process. In combination with an amorphous or crystalline silicon active matrix read out electronic the color sensors permit the realization of imagers with a high area fill factor, reduced pixel pitch and a good color resolution. The nipiin and piiin structures are very good candidates for low cost applications, which require a moderate color separation and no real time processing of the sensor data. The multi-layer structure based on vertically stacked diodes is more complex but the high flexibility in tuning the spectral sensitivity reveals high-end applications like multi spectral technology or document archiving.

6. Acknowledgements

The authors thank M. Krause, B. Rech, H. Siekmann (Research Center Juelich, IPV), J. Zimmer (Infineon, Munich), P. Herzog (University of Technology Aachen) for many helpful discussions. The work was partly supported by the Ministerium für Bildung, Wissenschaft and Technologie (BMBF).

7. References

/1/ P. Seitz, D. Leipold, J. Kramer, J.M. Raynor, "*Smart optical and image sensors fabricated with industrial CMOS/CCD semiconductor*", SPIE Vol. 1900, p. 21 (1993).

/2/ D.P. Poenar, R.F. Wolfenbuttel, "*Thin-film optical sensors with silicon compatible materials*", Appl. Opt. Vol. **36**, No. 21, p. 5109 (1997).

/3/ T. Neidlinger, M. Schubert, G. Schmid, H. Brummack, "*Fast color detection with two-terminal piin devices*", Mat. Res. Soc. Symp. Proc. **420**, 147 (1996).

/4/ J. Zimmer, D. Knipp, H. Stiebig, H. Wagner, "*Amorphous silicon based unipolar detector for color recognition*", IEEE Trans. Electron Devices Vol. **45** No. 5, 884 (1999).

/5/ P. Rieve, M. Sommer, M. Wagner, K. Seibel, M. Böhm, "*A-Si:H color imagers and colorimetry*", J. Non Cryst. Solids **266-269**, 1168-1172 (2000).

/6/ H.K. Tsai, S.-C. Lee, "*Amorphous SiC/Si three-color detector*", Appl. Phys. Lett. **52** (4), 275 (1988).

/7/ H. Stiebig, J. Giehl, D. Knipp, P. Rieve, M. Böhm, "*Amorphous silicon three color detector*", Mat. Res. Soc. Symp. Proc. **377**, 517 (1995).

/8/ D. Knipp, H. Stiebig, H. Wagner, "*Stabilized three-color piinip sensor for high illumination conditions*", Mat. Res. Soc. Proc. **507**, 225 (1998).

/9/ F. Palma, "*Multilayer color detectors, Technology and Applications of Amorphous Silicon*", Editor R.A. Street, Springer Series in Material Science **37**, Springer-Verlag, Berlin, p.306-338 (2000).

/10/ D. Knipp, H. Stiebig, Fölsch, H. Wagner, "*Four terminal color detector for digital signal processing*", J. of Non-Cryst. Solids, **227-230** 1321 (1998).

/11/ M. Topic, F. Smole, J. Furlan, W. Kusian, "*Stacked a-SiC:H/a-Si:H heterostructures for bias-controlled three color detectors*", J. Non-Cryst. Solids, **227-230**, 1326-1329 (1998).

/12/ D. Knipp, P. Herzog, H. Stiebig, H. Siekmann, F. König, H. Wagner "*Three and six channel sensors: Realization and colorimetric characterization*" Mat. Res. Soc. Proc. **558**, 279 (2000).

/13/ R.A. Street, *Hydrogenated Amorphous Silicon*, Cambridge University, Cambridge, UK, 1991

/14/ W. Luft, Y. Tuso, *Hydrogenated amorphous silicon alloy deposition processes*, Marcel Dekker, Inc., 1993.

/15/ R.L. Weisfield, "*a-Si:H linear and 2-D image sensors*", J. Non-Cryst. Solids, **164-166**, 771-776 (1993).

/16/ H. Fischer, J. Schulte, P. Rieve, M. Böhm,"*Technology and performance of TFA (thin film on ASIC)-sensors*", Mat. Res. Soc. Symp. Proc., **336**, 867-872 (1994).

/17/ O. Kluth, A. Löffl. S. Wieder, C. Beneking, L. Houben, B. Rech, H. Wagner, S. Waser, J.A. Selvan, H. Keppner, "*Textured etched Al-doped ZnO: A new material for enhanced light trapping in thin film solar cells*", Proc. 26th IEEE PVSEC, pp. 715-718 (1997).

/18/ J. Fölsch, F. Finger, T. Kulessa, F. Siebke, W. Beyer, H. Wagner, "*Improved ambipolar diffusion length in a-$Si_{1-x}Ge_x$:H alloys for multijunction solar cells*", Mat. Res. Soc. Symp. Proc. **377**, p.517 (1995).

/19/ G. Wyszecki, W.S. Stiles, John Wiley & Sons, USA, 1982.

/20/ D. Knipp, H. Stiebig, J. Fölsch, R. Carius, H. Wagner, "*Improved concept for nipiin and piiin color sensitive two-terminal devices with high linearity*", Mat. Res. Soc. Symp. Proc. **467**, p.931 (1997).

/21/ D. Knipp, H. Stiebig, J. Fölsch, F. Finger, H. Wagner, "*Amorphous silicon based nipiin structures for color detection*", J. Appl. Phys. **83** (3), p. 1463 (1998).

/22/ B. Stannowski, H. Stiebig, D. Knipp, Wagner, "*Transient photocurrent of three-color detectors based on amorphous silicon*", J. Appl. Phys. Vol. **85** No. 7, 3904 (1999).

/23/ M. Mulato, F. Lemmi, J. Ho, R. Lau, J.P. Lu, R.A. Street, "*Two-color amorphous silicon image sensor*", J. Appl. Phys. 90, 1589 (2001).

/24/ T. Neidlinger, R. Brüggemann, H. Brummack, M.B. Schubert, "*Color separation in a-Si:H based p-i-i-n sensors: Temperature and intensity dependence*", J. Non-Cryst. Solids, **227-230**, 1335-1339 (1998).

/25/ H. Stiebig, D. Knipp, P. Hapke, F. Finger, "*Three color p-i-i-i-n-detector using microcrystalline silicon*", J. Non-Cryst. Solids, **227-230**, 1330-1334 (1998).

/26/ Sony color CCD, Data sheet ILX524K.

/27/ D. Knipp, H. Stiebig, P. Herzog, "*Design and modelling of optical sensors in multi-channel Technology*", Mat. Res. Soc. Symp. Proc. **664**, in print.

H. Stiebig, D. Knipp, H. Wagner
Forschungszentrum Jülich, Institute of Photovoltaic,
52425 Jülich, Germany
Tel.: ++49 2461 612954,
Fax: ++49 2461 613735
E-mail: h.stiebig@fz-juelich.de

Prispelo (Arrived): 10.09.01 *Sprejeto (Accepted): 01.10.01*