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Signed this 8th day of September 1998

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PCT

GM/CHV/F64-2/cE

ECGM

THREE-COLOUR SENSOR WITH A PIN- OR NIP-SERIES OF LAYERS

The invention relates to a structure with several i-layers, which is limited on one side by a p-layer and on the other side by an n-layer, in accordance with the preamble of Claim 1. The invention additionally relates to a component containing such a structure, in particular a multiple colour sensor based on a pin- or nip-structure, in accordance with the preamble of Claim 10. The invention additionally relates to a process for the production of such a structure in accordance with the preamble of Claim 11.

Structural elements based on amorphous silicon or its alloys, comprising two antiseriably arranged pin- or nip-diodes for the formation of a pinip- or nipin-structure, are known as state of the art. In this case, the diodes are arranged essentially vertical to the direction of light incidence.

Such a nipin-structure as amorphous silicon-based photosensitive electronic component is known, for example, from US patent 53 11 047. Moreover, to optimise such a nipin-structure with respect to the spectral response dependent on the voltage applied to this structure, the following is known:

The blue/green sensitivity in the nip-structure sequenced upline in the direction of light incidence or the red/green separation in the pin-structure sequenced downline in the direction of light incidence can be improved by installation of additional intrinsic layers on both sides of the p-doped layer with a band gap of between 1.74 eV and 1.9 eV. (Q. Zhu, H.Stiebig, P.Rieve, J.Giehl, M.Sommer, M.Böhm, "NEW TYPE OF THIN FILM IMAGE SENSOR" in Sensors and Control for Advanced Automation, edited by M.Becker, R.W.Daniel, O.Loffeld, Proc. SPIE 2247 (1994) 301).

It is known to absorb preferably blue light in the first intrinsic layer, green light in the front part of the intrinsic layer of the

rear diode, and red light by reduction of the $\mu\tau$ -product in the rear part of the second intrinsic layer. For this, a nipin-structure is used wherein one or more additional i-layers are provided. (H.Stiebig, J.Giehl, D.Knipp, P.Rieve, M.Böhm, AMORPHOUS SILICON THREE COLOR DETECTOR in MRS Symp. Proc. 377 (1995) 813 or H.Stiebig, C.Ulrichs, T.Kulesa, J.Fölsch, F.Finger, H.Wagner, TRANSIENT PHOTOCURRENT RESPONSE OF A-SI:H BASED THREE COLOR NIPIN DETECTORS, in ICAS 16, Kobe, Japan. September 4-8, 1995). Therein, τ is the service life of the charge carrier generated by the incident light and μ its mobility.

A disadvantage in the known named components is that only up to three linearly independent spectral response curves are detected by the structure of the layer system. Consequently, a comparatively expensive superposition of these three independent signals is necessary for colour image processing.

Therefore the object of the invention is to provide a structure with several i-layers, in which independent signals are received such that a reduced superposition is required with a view to avoiding such a superposition.

In addition, the object of the invention is to provide an inexpensive optoelectronic component, in particular a multiple colour sensor, suited to continuously displacing its spectral response by variation of the voltage applied, and thus to obtain a spectral response meeting the desired boundary conditions, in particular to thus detect more than three linearly independent curves of the spectral response in the range from uv to near ir incident light and thereby achieve a reduction in the superposition requirements.

The object is achieved by a structure in accordance with all the features of Claim 1. The object is additionally achieved by a component in accordance with all the features of Claim 10. The

object is furthermore achieved by a process in accordance with all the features of Claim 11. Further expedient or advantageous embodiments or variants are to be found in the sub-claims respectively referring to one of these claims.

It has been recognised that to extend the operability of a component containing such a structure from the direction of light incidence, the respective band gap E_g of the individual i-layers generally decreases as a result of suitable selection of the alloys, while the transport characteristics (which can be characterised by means of the product $\mu\tau$) of the photogenerated charge carrier improve for a nipin-structure in both intrinsic layer systems of the top and bottom diode in the direction of the p-layer (see Figure 1). For a pinip-structure as in the case of the nipin-structure the band gap of the individual layers is generally reduced from the direction of light incidence by suitable selection of the alloys, while the $\mu\tau$ increases from the n-conducting layer to both p-conducting layers.

The term "generally" is used in the above sense to mean that it has been recognised that at least in the boundary area of two adjacent i-layers the conditions formulated in the main claim should be met for the band gap and the transport characteristics. In this case, the value of the band gap and the transport characteristics can be kept constant in an advantageous manner within the respective i-layer. It is nevertheless conceivable to permit a limited variation of the respective value within the respective i-layer.

Moreover, the collection of charge carriers can be influenced by a modification of the electric field (e.g. by micro-doping of the i-layers) in order to further vary the spatial charge carrier collection in this way.

It has been additionally recognised that the structure is not thereby restricted to structures of the nipin or pinip type; rather, and also expressly included in the invention, there are surprisingly simple structures and components containing such a structure of the type of a simple pin- or nip-structure. Advantageously, a single polarity is sufficient in such a structure in contrast to the antiseriably connected double diodes of the type of a pinip- or nipin-structure apparently considered necessary.

By variation of the voltage applied to the pin-, nip-, pinip- or nipin-structure according to the invention, the spectral response can be displaced in the region of far ultraviolet (uv) as far as the near infrared (ir) with this structure or this component, and the desired boundary conditions can be adjusted accordingly.

In an advantageous manner, the structure according to the invention may be formed in such a way that it renders the detection of light of different wavelengths continuously adjustable by variation of the voltage applied to the structure and thus in consequence at least reduces the required superposition.

The invention shall be explained in more detail below on the basis of figures and embodiments:

Figure 1 is a local curve of the band gap E_g and the product $\mu\tau$ of a nipin-structure according to the invention suitable for forming a colour sensor, for example;

Figure 2 shows the spectral response of a nipin-structure according to Figure 1;

- Figure 3 shows defect density N_D as a function of the optical band gap for $a\text{-Si}_{1-x}\text{Ge}_x\text{:H}$, wherein in the insertion the optical band gap is represented as a function of the germanium content in the material;
- Figure 4 shows photo- ((O) or AM 1.5) and dark conductivity ($\bullet$) σ as a function of the optical band gap E_g for $a\text{-Si}_{1-x}\text{Ge}_x\text{:H}$;
- Figure 5 ambipolar diffusion length L_{ambi} as a function of the optical band gap E_g for $a\text{-Si}_{1-x}\text{Ge}_x\text{:H}$ in comparison to values known from the literature [3, 4, 5];
- Figure 6 shows the photo-conductivity σ as a function of the optical band gap E_g for $a\text{-Si}_{1-x}\text{C}_x\text{:H}$, produced from a silane/methane mixture, with (o) and without ($\bullet$) hydrogen dilution; circles according to [6], squares according to [2];
- Figure 7 shows the influence of micro-doping on the electric field for a nip-structure with three i-layer regions I, II and III, which have a different transport ($\mu\tau^{\text{I}}$, $\mu\tau^{\text{II}}$, $\mu\tau^{\text{III}}$) behaviour for charge carriers;
- Figure 8 shows the band gap profile and variation in transport characteristics of a colour sensor based on a pin-structure;
- Figure 9 shows the voltage-dependent spectral response of a unipolar colour sensor based on a pin-structure with three i-layer regions.

Embodiments

Figure 1 shows a structure of the nipin type in cross-section with top and bottom diode constructed consecutively in the direction of light incidence (from left to right). The top diagram therein shows the curve of the band gap E_g , the bottom diagram the curve of the transport characteristics $\mu\tau$ as a function of the local coordinate x in the layer sequence.

The top diode contains a nip-structure with two i-layers i^I and i^{II} . These are constructed therein such that they have a band gap $E_g^I = 2.0$ eV and $E_g^{II} = 1.95$ eV respectively. These two layers were produced by means of a silane/methane mixture in the ratio 20 sccm / 20 sccm for i^I and 4 sccm / (4 sccm with 180 sccm H_2) for i^{II} respectively. Constant values for E_g and $\mu\tau$ were adjusted within the respective i-layer in the case of both the top and the bottom diode.

The rear bottom diode contains a pin-structure with three i-layers i^{III} , i^{IV} and i^V . These are constructed thereby such that they have a band gap $E_g^{III} = 1.9$ eV, $E_g^{IV} = 1.65$ eV and $E_g^V = 1.50$ eV respectively. These i-layers i^{III} , i^{IV} and i^V were formed from amorphous Si(C), a-Si_{1-x}Ge_x (with $x=0.5$) and a-Si_{1-x}Ge_x (with $x=0.20$) respectively.

In Figure 2, it is demonstrated with a structure according to Figure 1 as an example of a 5-colour sensor how the spectral response of a wavelength of 470 nm (collection of all generated charge carriers in the front top diode) can be displaceably adjusted from positive higher voltages to 500 nm for low positive voltages.

As a result of different $\mu\tau$ products in the intrinsic layers of the top diode the photogenerated electron hole pairs are collected in the rear portion of the intrinsic i-layer (region $\mu\tau^{\text{II}}$) at lower positive voltages, while the generated charge carrier pairs recombine in the region of the lower $\mu\tau$ product.

The different $\mu\tau$ products are achieved, for example, by the use of materials produced with different hydrogen dilution. Only at higher positive voltages does the electric field increase over the top diode and the charge carrier pairs can be collected in the front region of the intrinsic i-layer of the top diode.

For negative voltages or for the rear bottom diode, three different regions with different $\mu\tau$ product were selected. By applying negative voltages, the bottom diode is in non-conducting direction, and the photogenerated charge carriers can be collected in this diode. For low negative voltages, the charge carrier pairs are collected in the region $(\mu\tau)^{\text{III}}$ (maximum of the spectral response at 550 nm), while they recombine in all other regions $((\mu\tau)^{\text{IV}}$ and $(\mu\tau)^{\text{V}})$ by the installation of material with a lower service life. If the electric field above the intrinsic layer in the bottom diode is increased, the charge carriers are collected in the regions with $(\mu\tau)^{\text{III}}$ and $(\mu\tau)^{\text{IV}}$, while the photogenerated charge carriers continue to recombine in the region with $(\mu\tau)^{\text{V}}$ (maximum of the spectral response at 595 nm).

At an even higher applied negative voltage, all the photogenerated charge carriers are collected in the bottom diode and a further maximum in the spectral response at 650 nm is observed. Thus, at voltage values of +3V, 1V, -1V, -2V and -4V, for example, linear independent curves of the spectral response can be respectively detected.

Through many further i-layer regions respectively with different transport characteristic ($\mu\tau$ product), it is possible in this way to achieve an essentially continuous voltage-dependent spectral response. In this case, a structure with very many i-layers with respectively different band gap and transport characteristics is equal to a structure with one i-layer with a variable band gap and/or transport characteristic within this. This embodiment is also regarded as coming under the subject matter of the drawn up claims and is claimed as such.

The transport characteristics can be adjusted or varied, for example, by means of one or more of the following measures:

- a) inclusion of germanium (Ge), carbon (C), nitrogen (N) or oxygen (O) into the amorphous silicon network, e.g. a-SiGe:H, a-SiC, a-SiH, a-Si_{1-x}N_x:N or a-Si_{1-x}O_x:H;
- b) addition of hydrogen or variation of the hydrogen concentration in the process gases both for a-Si:H and for its alloys, as specified under point a);
- c) variation of the process parameters, such as pressure, temperature or power, for example.

The production conditions can have the following influence on the transport characteristics of a-Si:H-based alloys:

In the case of amorphous silicon (a-Si:H) the optoelectronic characteristics can be influenced by variation of the production conditions. For example, the material quality can be changed by variation of the deposition pressure, temperature, the electric power supplied or by suitable addition of additional process gases (e.g. hydrogen, helium, argon, fluorene) in the layer deposition process. This means that the transport characteristics of the

charge carrier (i.e. the product from the service life of the charge carrier and the mobility of the charge carrier as well as the ambipolar diffusion length) can be purposefully adjusted.

In the case of the alloys of amorphous silicon, e.g. the silicon-germanium alloys ($a\text{-Si}_{1-x}\text{Ge}_x\text{:H}$) and the silicon-carbon alloys ($a\text{-Si}_{1-x}\text{C}_x\text{:H}$), the transport characteristics change with the composition of the respective alloy. This behaviour is shown by the example of the silicon-germanium alloy in Figures 3 to 5.

As the germanium content increases, the optical band gap can be continuously adjusted between $E_g \approx 1.8$ eV ($a\text{-Si:H}$) and $E_g \approx 1.0$ eV ($a\text{-Ge:H}$), as may be seen from the insertion in Figure 3. As the Ge-content increases, the defect density, determined by the measurement process referred to as "constant photocurrent method", increased by two orders of magnitude or more (Figure 3, large figure). At the same time, the photo- and dark conductivity (see Figure 4) and also the ambipolar diffusion length (see Figure 5) change in dependence upon the alloy composition. The photoconductivity is thereby proportional to the product from charge carrier service life τ and mobility μ and reflects the transport characteristics of the majority charge carriers (in this case: electrons). The ambipolar diffusion length thereby essentially describes the transport characteristics for the minority charge carriers (in this case: holes) for the material present here.

In addition, the transport characteristics can be influenced in the case of the silicon alloys (as with $a\text{-Si:H}$) by preparation measures (as described above), in particular by the addition of additional process gases during deposition [Matsuda 1, 2]. The influence of the addition of hydrogen ("hydrogen dilution") to the process gases silane (SiH_4) and methane (CH_4) is shown in Figure 6

as an example for the alloy system $a\text{-Si}_{1-x}\text{C}_x\text{:H}$. Material produced with heavy hydrogen dilution exhibits an essentially higher photoconductivity and thus higher values for the $\mu\tau$ product than in the cases where deposited material without H_2 addition is used. This effect thereby increases intensely as the C (carbon) content increases. The ratio of $[\text{H}_2]$ to $([\text{SiH}_4]+[\text{CH}_4])$ can thereby assume values, for example, of 10 to 50.

It is known from the literature and from publications concerning pin solar cells that the collection of blue light in pin-diodes can be reduced by a carry-over of doping gas (such as boron) in the front region and be increased, for example, by phosphorous doping in the i-layer. By the combination of micro-doping with simultaneous variation of the band gap E_g and the transport characteristic in the individual i-layers, the spectral colour separation can be further improved. This is explained on the basis of the top diode (nip-structure) of a nipin-structure (Figure 7, Figure 8).

Figure 7 shows the curve of the band gap E_g and the transport characteristics $\mu\tau$ as a function of the coordinates of a nip-structure according to the invention with three i-layers.

A positive fixed charge is incorporated into the absorber layer by including phosphorous (Figure 7, curve 1). The electric field is thus increased in the region of the p/i-transition, while it is reduced in the other portion of the absorber layer (in the region of the i/n transition). The position-dependent collection is thus supported by the position-dependent field curve. The opposite influence is observed for inclusion of boron (Figure 7, curve 2).

Corresponding optimisation of the colour separation, for example, by the inclusion of phosphorous, can naturally also be undertaken

in the nipin- or in the intrinsic i-layers of a pinip-structure.

In addition, the field, and thus the wavelength-dependent collection efficiency, can also be changed or adjusted by means of a partial doping of individual i-layers of the modified absorber layer (e.g. with boron, phosphorous, arsenic or fluorene).

The following is also stated concerning the multiple colour sensor based on a nip- or pin-structure such as may be seen from Figure 7 or Figure 8, for example:

The nip- or pin-structure according to the invention which is suitable as photodiode, its spectral response being displaceable by variation of the applied voltage, allows the formation of a unipolar detector, in which only a single polarity of the voltage applied to the structure is required to detect the three known colours (red, green and blue), other colours or even several of these colours.

Since three or more colours can be detected in the above-specified manner with the structure according to the invention in a bottom diode, for example, because of three independent equations, a structure based on a pin- or nip-layer sequence respectively with several i-layers is already sufficient. On this basis, by the solution to the set problem, it thus decisively exceeds the characteristics of the structurally far more complex, antiseriial pinip- or nipin-layer sequence described as known. A unipolar three- or multiple-colour sensor based on a pin- or nip-structure, in particular based on amorphous silicon or its alloys, is also achieved according to the invention.

Such a structure suitable for formation of a sensor also has the advantage that on construction of a sensor array using such a structure, a clearly reduced coupling of adjacent pixels occurs,

since in comparison to a nipin- or pinip-structure, this structure has no conductive middle layer in the form of the adjacent p- or n-layer on both sides of i-layers. Moreover, only a single polarity is advantageously necessary for the applied voltage.

Moreover, with the structure according to the invention the transient behaviour in relation to a detector based on two antiseriial diodes is improved, since charging processes of the stored charge do not occur in the top or bottom diode, as are observed with pinip- or nipin-structures.

The use of three or more i-layer regions respectively with different $\mu\tau$ product can be conceivable and also desired thereby. Analogous to the nipin-structure micro-doping can be performed for optimisation. Phosphorous, boron or arsenic can be used for such a doping.

In the case of a pin-structure, the band gap E_g is reduced in the direction of incident light at the boundary areas of two adjacent i-layers. The absorber layer is divided into three regions with a different $\mu\tau$ product, whereby the transport characteristics of the materials used also deteriorate from the p-conducting layer to the n-conducting layer, as is shown in Figure 8. Measurement results for a structure are shown in Figure 9 which for increasing negatively applied voltage demonstrate the displacement of the spectral response and its purposeful adjustability as a function of the wavelength of the light.

In the case of a nip-structure, the band gap is also reduced from the direction of light incidence (n-layer), while the transport characteristics improve in the three different regions of the n-layer to the p-layer.

The following is stated with respect to Figure 10, in which a sensor line or a sensor array of the type nipin- or pin-colour sensor is shown:

In unstructured sensor arrays or sensor lines, the high conductivity of doped n- and p-layers leads to coupling currents perpendicular to the direction of light incidence. The area of an active pixel in an unstructured sensor array is defined by its back contact (structured metallising plane). An occurring coupling current (I_q) superposes the photo-current and makes the evaluation of the signal difficult or prevents it. Coupling processes over the n-layer (last semiconductor layer before the back contact) in the case of a nipin- or pin-diode (the p-layer accordingly in the case of a pinip-detector) can be prevented by technological measures (e.g. inverted deposition on a structured substrate, in which the n-layer tears off at previously defined pixel edges) or by the switching ($U_1 = U_2 = U_3 \dots$). The coupling via the p-layer in the case of a nipin-detector (accordingly the coupling via the n-layer in the case of a pinip-diode) can only be prevented by a complete structuring (removal of the thin-film system between individual pixels) of the array or by transfer to a unipolar detector (pin- or nip-diode), in which the complex i-layer system in the component is only interrupted by a layer with high conductivity. Since structuring of the complete array is technologically time-consuming and costly, an unstructured sensor array comprising pin- or nip-diodes, which can separate three or more spectral components of the light, constitutes an advance with respect to the reduction of the coupling current.

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**Patent Claims:**

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1. Structure with several i-layers, which is limited on one side by a p-layer and on the other side by an n-layer, characterised by means for forming these i-layers in such a way that:
 - at least in the boundary area between two adjacent i-layers (i^I , i^{II}), viewed in the direction of light incidence, the band gap $E_g(I)$ of the respective first i-layer (i^I) more closely adjacent to the light input side is larger than the band gap $E_g(II)$ of the second i-layer (i^{II}) further removed from the light input side,
 - at least in the boundary area between two adjacent i-layers (i^I , i^{II}), in the direction from the p-layer to the n-layer, the product $\mu\tau(I)$ of the i-layer (i^I) further removed from the n-layer is larger than the product $\mu\tau(II)$ of the i-layer (i^{II}) more closely adjacent to the n-layer.
2. Structure according to Claim 1, characterised by a pin- or nip-structure.
3. Structure according to Claim 1 or 2 with a majority of i-layers or a plurality of i-layers (I, II, ...).
4. Structure according to Claim 1, 2 or 3, wherein in one or more i-layers, in particular in all i-layers (I, II, ...), the respective band gap $E_g(I, II, \dots)$ within this i-layer has a constant value.
5. Structure according to Claim 1, 2, 3 or 4, wherein in one or more i-layers, in particular in all i-layers (I, II, ...),



the respective product $\mu\tau(I, II, \dots)$ within this i-layer has a constant value.

6. Structure according to Claim 1, 2, 3, 4 or 5, wherein to form a pinip-structure, the n-layer on the side adjacent to the i-layer has a further layer sequence with one or more i-layers as well as a further p-layer limiting this further layer sequence.
7. Structure according to Claim 1, 2, 3, 4 or 5, wherein to form a nipin-structure, the p-layer on the side adjacent to the i-layer has a further layer sequence with one or more i-layers as well as a further n-layer limiting this further layer sequence.
8. Structure according to Claim 6 or 7, characterised by means for constructing the further layer sequence in such a way that:
 - at least in the boundary area between two adjacent i-layers (i^I, i^{II}) of this further layer sequence, viewed in the direction of light incidence, the band gap $E_g(I)$ of the respective first i-layer (i^I) more closely adjacent to the light input side is larger than the band gap $E_g(II)$ of the second i-layer (i^{II}) further removed from the light input side,
 - at least in the boundary area between two adjacent i-layers (i^I, i^{II}) of this further layer sequence, in the direction from the p-layer to the n-layer, the product $\mu\tau(I)$ of the i-layer (i^I) further removed from the n-layer is larger than the product $\mu\tau(II)$ of the i-layer (i^{II}) more closely adjacent to the n-layer.



9. Array with a plurality of structures respectively forming one pixel according to one of Claims 1 to 8.
10. Electronic component, in particular a multiple colour sensor, containing one or more structures according to one or more of Claims 1 to 9.
11. Process for the production of a structure according to one of Claims 1 to 9, characterised in that
 - a structure with several i-layers is formed, which is limited on one side by a p-layer, on the other side by an n-layer, and means are thereby selected for forming these i-layers in such a way that
 - at least in the boundary area between two adjacent i-layers, viewed in the direction of light incidence, the band gap $E_g(I)$ of the respective first i-layer more closely adjacent to the light input side is larger than the band gap $E_g(II)$ of the second i-layer further removed from the light input side,
 - at least in the boundary area between two adjacent i-layers (i^I , i^{II}), in the direction from the p-layer to the n-layer, the product $\mu\tau(I)$ of the i-layer (i^I) further removed from the n-layer is larger than the product $\mu\tau(II)$ of the i-layer (i^{II}) more closely adjacent to the n-layer.