Multispectral matrix silicon photodetectors with the IR range registration

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Abstract. The paper presents a multi-layer digital camera matrix photodetectors modifications. Modifications are a matrix photodetectors two main types hybrid: spatial structure and multilayer. The matrix photodetectors issue current state with the registering images function in both the visible and IR range is considered in detail. Such well-known manufacturers photomatrices analysis is carried out. To obtain a multispectral image, it is proposed to introduce light-sensitive layers for the near and mid-IR ranges. The developed matrices patterns are presented that allow achieving a balance of each of the five channels (red, green, blue, near and mid-IR) so that the spectrum each selected range has the matrix surface equal share. A layers' combination is also proposed that allows to apply them separately—a layer that will minimize the noise in this area and focus on the infrared region, and use the visible one as an auxiliary one. At the same time, to get a full-fledged image, you need to apply each pixel interpolation. The light-sensitive layers’ distribution principle in each pattern is described.

1. Introduction

At the moment there is colour separation systems development for the matrix of photodetectors used in cameras and camcorders. The main mass is colour separation systems based on light filters. There are only photodetectors few variants that use multilayer structures as colour separators.

Even though such developments began in the late 90s, technologies began to develop in this direction only in the 2000s, and matrix photodetectors manufacturers were in a hurry to register their applications for patenting such developments. We will mainly focus on photodetector matrices based on silicon, the layers of which are alternately doped with n- and p-type impurities, and the multicolour is due to the radiation penetration different depth with different wavelengths into the thickness of the semiconductor.

To create a multicolour photodetector, wider-band materials layers must be placed on top. But semiconductors on silicon epitaxial growth is a very difficult task, which is currently only beginning to be solved. Therefore, multilayer matrices are not widely used, but they are very promising.

This work purpose is to develop patterns for a colour separation system for a multi-layer matrix photodetector with a multispectral radiation detection function. The authors propose to consider semiconductors multilayer structures modern types in matrix image registration systems and suggest patterns with both visible and infrared ranges registration.
2. The issue current state analysis

Foveon introduced its development called Foveon X3 back in 2001. The technology essence is to apply a physical phenomenon in the semiconductor itself: as the wavelength increases, the photon penetration depth into the semiconductor increases. Thus, to capture blue, green and red colours photons, photodiodes created by the first and second types alternating conduction bands are placed one under the other at certain depths. This results in a universal sensor that registers information about the image of all three colour components at a single point [1, 2].

The layer thickness and material are selected in such a penetrating photons separation way that occurs exactly in the three spectral ranges that contain the main colours.

Layers are included in each other, alternating by the main media (n-type and p-type) type. Each subsequent layer forms a new potential well (for electrons or "holes"). Compared to traditional sensors with mosaic filters, X3 matrices receive three times more light information and generate images with twice the resolution.

X3 also can change the photocell size (Variable Pixel Size-VPS). Combining a solar cells group into one superpixel increases the signal-to-noise ratio, providing better shooting in low-light conditions, reduces frame acquisition time, and speeds up the autofocus process.

The VPS photodetector is a hybrid product new class that normally operate as a digital video camera with a sensitive layer increased area. This structure works well when shooting fast-moving objects or low-light scenes.

The multilayer matrices main drawback is that the excess charge can flow not only to neighbouring cells but also to "foreign" layers, i.e. bluming becomes "three-dimensional". Also, the multi-layer systems' disadvantage is each layer noise.

Knowing about the Foveon X3 matrix shortcomings, California engineers at the end of 2003 presented to the public a Foveon X3 Pro 10M photo sensor improved version. The new matrix differed from the previous version primarily in its sensors each was additionally "covered" with a microlens. This improvement made it possible to significantly increase the sensors' sensitivity and, as a result, dramatically improve the photographed object colour reproduction. With 3.46 million sensors in the matrix each layer, the new Foveon X3 Pro 10M photo sensor contained 10.6 million sensitive elements – three times more than CMOS or CCD counterparts (according to marketers). However, this did not make it 10-"megapixel", since due to the inevitable power losses when the light stream passes through layers and filters, the captured image gave about 70% of the quality that could be expected from a matrix with 10 million sensors. Thus, the new photo sensor resolution was approximately equivalent to a 7-megapixel CMOS or CCD analogue. That is why Foveon very carefully avoided the issue of Foveon X3 Pro 10M resolution, emphasizing that since the photosensor was built on a unique technology basis, it is necessary to evaluate its advantages with unique "lines" [1].

Also, relatively recently, the TFA (Thin Film on ASIC) technology was patented. TFA is the integration of amorphous hydrogenated silicon (a-Si: H) detector layer onto an ASIC (Application Specific Integrated Circuit, essentially a CMOS chip) [1, 3].

The detector layer is less than one micrometre thick and works as a multispectral photodiode. The spectral sensitivity peak can shift within the visible spectral range depending on the voltage between the p- and n-regions. You can read three-colour components sequentially, quickly changing the voltage. Other than this a-Si:H has a high quantum yield and three linearly independent sensitivity peaks in the spectrum visible part.

The TFA is a sensor with a 100% fill factor since the entire surface is light-sensitive. It is assumed that TFA sensors will provide an increase in the dynamic range of up to 120 dB (with the human eye capabilities in 200 dB) and will increase the colour resolution. One of the technology disadvantages is the production high cost, so the development is not widely used.

It is possible to exclude the described disadvantages by taking into account the difference in the short-wave and long-wave radiation penetration depth in semiconductors and by increasing the light-sensitive layers' area.
In the proposed method, multi-element matrix photodetector devices (MMPDs) for dividing light into primary colours have a multi-layer structure based on thin films. The layers thickness and material are selected in such a way that the penetrating photons’ separation occurs precisely in the three spectral ranges that contain the system main colours: blue (B), green (G) and red (R). The first layer (p-type), located under the polycrystalline electrode, absorbs the spectrum blue component, passing the green and red components. The second layer (n-type) absorbs the green component and passes the red one. The third layer (n-type), located in the p-type substrate, absorbs the spectrum red component. Thus, each layer accumulates a charge that carries information about only one of the colours.

The semiconductor only two layers use solves the excess carriers’ drainage problem in the matrix photodetector, and also reduces the noise level by using a layers smaller number. The semiconductor only two layers use solves the excess carriers’ drainage problem in the matrix photodetector, The proposed photosensitive layers combinations allow:

- to reduce the noise due to the layers smaller number in the sensor;
- apply different drainage systems to the matrix all layers to avoid three-dimensional blooming;
- get basic colours different combinations, which expands the developed matrix photodetectors applications range;
- simplify the mathematical apparatus (algorithm) for calculating colours (interpolation, antialiasing, etc.).

Currently, active scientific work is underway to combine the visible and infrared spectra to obtain multispectral images in various ways. The proposed methods are based either on combining several devices with different functions or on using different algorithms for processing standard image recorders [4-6].

Innovations in the multilayer matrices’ topic is a multispectral receiver development that includes sensors in both the visible and IR ranges. It is proposed to develop multi-layer receivers with the red, green, blue spectrum layers simultaneous inclusion, as well as in the near and middle IR range.

In 2015, Sony introduced its new RGB-IR sensor (https://www.ovt.com/purecel-pixel-tech/rgb-ir-technology/faqs) (figure 1).

![Figure 1. Sony RGB-IR sensor.](image)

This is an image sensor with elements that are susceptible to infrared radiation. Sony engineers replaced half of the green (G) colour filters with white (W) ones. In addition to the three main colours, there is also a white filter. As a result, a colour image can be created without an IR filter. It is believed that the new technology allows you to create a picture using not only visible but also infrared radiation, by
replacing the colour filter and reworking the software. However, this technology is based on a spatial colour separation system. Therefore, as a result, the resolution, at best, will be the same.

Therefore, the proposed developments will improve the matrix image quality while simultaneously working in both the visible and IR range, which significantly expands such systems scope.

3. Multispectral photodetector patterns development
Previously, multilayer matrix modifications *Foveon X3* [7, 8] were proposed, where the layers fit into each other, alternating according to the main carriers' type (*n*-type and *p*-type). Each subsequent layer forms a new potential well depending on the layer, for electrons or for "holes". The layer thickness and material are selected in such a penetrating photons' separation way that occurs exactly in the three spectral ranges that contain the main colours. To obtain an image with the most accurate colour component, the corresponding wavelength (which determines the radiation colour) photons absorption must occur in the corresponding layer at a potential well in silicon certain depth (figure 2) [9].

![Absorption depth in Silicon](image)

Figure 2. Silicon optical properties at a temperature of 300K.

Each matrix consists of a substrate of *p*-type, which contains layers of *n*-type. Further, layers *n*-type include materials *p*-type and so on. The proposed modifications with primary colours imply a reduction in the layers' number to two to reduce the matrix noise levels.

The new modification also supports the using only two layers' idea. To obtain a multispectral image, it is proposed to introduce light-sensitive layers for the near and mid-IR ranges, which can be realized on a silicon basis. In figure 3 and figure 4 shows patterns of four types.

The pattern cells combination based on MMPD-1 allows distributing the sensitive layers so that for each selected spectrum range there is the matrix surface equal fraction: 50% for the red - *R*, 50% for the green - *G*, 50% for the blue components - *B*, and also 50% for infrared radiation - *IR*. This balances each of the four spectrum bands. At the same time, to get a full-fledged image, you need to apply each pixel interpolation.

The MMPD-2 pattern includes the photosensitive area 100% coverage with cells sensitive to the IR region (*IR*), while the visible spectrum layers also occupy 100%: the green component capture cell 50%, the blue 25%, and the red 25%. This layers' combination will make it possible to obtain images in four spectral ranges at once, and the IR snapshot image will not require interpolation.
When the layers are aligned as shown on the MMPD-3 pattern, the layers B, G and IR each account for the sensitive matrix surface 50%, and the component R - 25%. The red component can be neglected because the human eye is less sensitive to this radiation area. But this combination allows you to use a separate layer IR, which will minimize the noise in this area, and will allow focusing on the infrared region, and use the visible one as an auxiliary one.

The MMPD-4 cells order assumes taking a picture both in the visible and in the near (NIR) and middle (MIR) spectrum infrared regions. Moreover, each layer is allocated the matrix 50%, except for layers R with 25% share, as in the previous case in the MMPD-3 pattern. However, additional materials and technologies may be required to implement the layer MIR.

In figure 3 and figure 4 the upper layers are shown much smaller than the lower ones, although this is technologically incorrect. Usually, the top layer is less than the previous one by no more than 10%.
A similar ratio as in the figures is given only for a proposed matrix type operation principle visual representation and the fact illustration that by excluding one layer, it is possible to increase the next sensitive area. For a more detailed analysis, it is necessary to research the light flux passage through the matrix with the recording infrared radiation function.

4. Conclusion

The proposed matrices make it possible to expand the radiation detectors functionality and obtain a multispectral image in one image both in the visible and infrared ranges. The multi-layered pattern system allows such a complex device resolution to be increased. Also, with an infrared image help, it will be possible to correct an image in the spectrum visible region: remove defects, artefacts, contamination on objects, etc.

The developed patterns allow you to achieve the five channels (red, green, blue, near and mid-IR) each balance so that the spectrum each selected range has the matrix surface equal share. A combination is also proposed that allows you to apply a separate IR layer, which will minimize the noise in this area and will allow focusing on the infrared region, and use the visible one as an auxiliary one. At the same time, to get a full-fledged image, you need to apply each pixel interpolation.

It is planned to apply interpolation various types to the developed patterns and to prove the algorithm simplification for processing the resulting image. It will also be possible to simulate an image obtained by similar types matrices, and by example to show a multilayer receiver operation principle and interpolation methods.

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