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Valerian Dorogan, Tatiana Vieru, Mihail Manole, Roxana Savastru, Tudor Zisu, "Ultraviolet radiation sensors on the basis of semiconductors," Proc. SPIE 4430, ROMOPTO 2000: Sixth Conference on Optics, (29 June 2001); doi: 10.1117/12.432818

Event: ROMOPTO 2000: Sixth Conference on Optics, 2000, Bucharest, Romania

Ultraviolet radiation sensors on the basis of semiconductors

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ABSTRACT

The paper deals with elaborating and manufacturing of new structure of UV radiation sensors on the basis of single-crystal Si. The structure consists of two photoactive cells, differentially connected to loading resistor. One cell is covered with a layer, transparent for visible and IR radiation and non-transparent for UV radiation. Differential connection excludes the common for both cells components. Thus, the photocurrent of differential sensor is proportional only to UV radiation intensity.

Keywords: UV radiation,UV sensors, Si crystal sensor

1. INTRODUCTION

The UV radiation sensors on the basis of semiconductors are destined to measure, in a portable UV dosimeter, the UV radiation of the sun and of another UV sources. The UV natural radiation is a part from the sun radiation. The sun's irradiance E just outside the earth's atmosphere, at mean earth-sun distance is[1]:

$$E = 1390\ \mathrm{W/m^2} = 139\ \mathrm{mW/cm^2}, \tag{1}$$

The irradiance is a radiometric quantity and SI unit is $[\mathrm{W.m^{-2}}]$. In terms of E_λ the sun spectral irradiance outside the atmosphere is:

$$E = \int_0^\infty E_\lambda d\lambda , \tag{2}$$

From the solar curve outside atmosphere and at sea level it is possible to estimate the UV natural radiation by some quick calculations.Thus for the solar irradiance outside atmosphere , considering in a first approximation a triangle results :

$$E' = 1400\ \mathrm{W/m^2} = 140\ \mathrm{mW/cm^2}, \tag{3}$$

Also, for the solar irradiance at sea level due to the average effect of atmospheric attenuation and absorption results:

$$E'' = 1050\ \mathrm{W/m^2} = 105\ \mathrm{mW/cm^2}, \tag{4}$$

The value of E from (1) and (2) are approximately equal, which is acceptable.

An extensive series of solar illuminance measurements at the earth's surface indicates an illuminance on a horizontal surface at sea level, with the sun at its zenith in a "comparatively clear" sky of:

$$E_v = 1.24 \times 10^5\ \mathrm{lm/m^2},$$

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The illuminance is a photometric quantity and the SI unit is $[lm.m^{-2}]$. As it was noted in equation (1), the maximum variation from the average caused by the yearly changes in distance of the earth from the sun is less than ± 3.5%. Solar irradiance on the earth's surface depends on the altitude angle of the sun above the horizon, on the observer's altitude above sea level, and upon the amount of dust, haze, and clouds in the sky. Also, the illuminance level on the surface of the earth due to the sun depends on the true altitude angle of the center of the sun as it's indicated in Fig.1. These levels are situated in the range of $6.10^{-4}....12.10^{4}$ lm/m^2 .

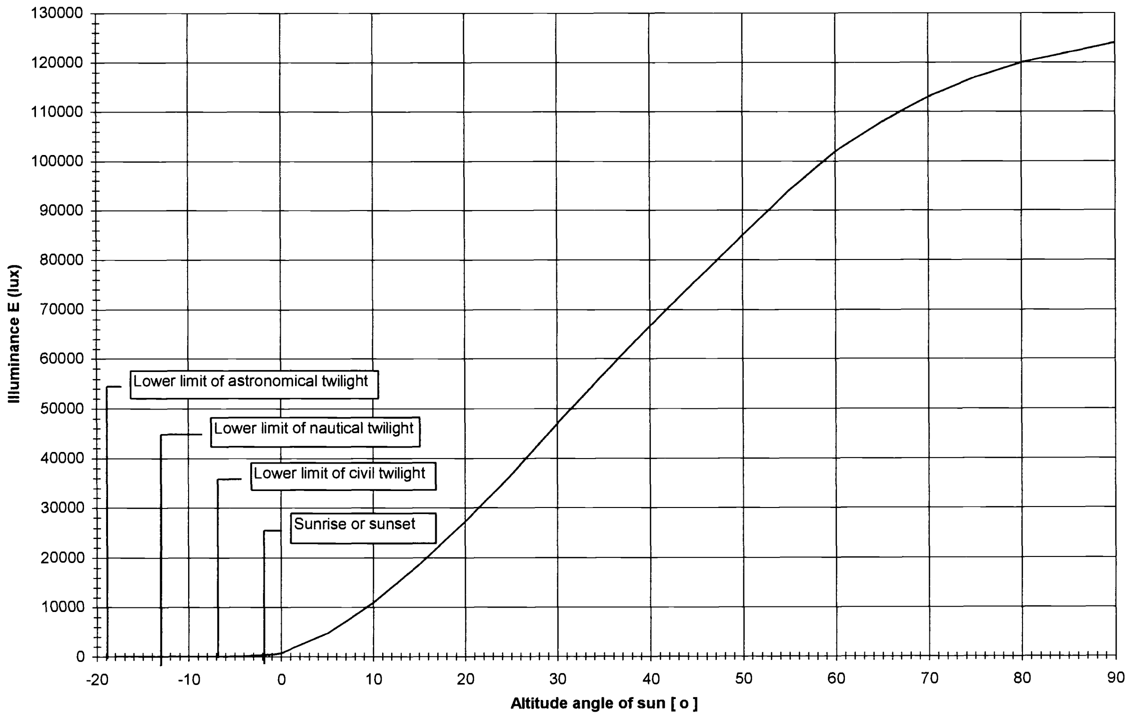

Fig. 1 Illuminance levels on the surface of the earth due to the sun

From the same curve it's possible to estimate the UV part from the sun's irradiance outside the earth's atmosphere :

$$E'_{UV} = 130\ W/m^2 = 13\ mW/cm^2 , \tag{5}$$

At the sea level results:

$$E''_{UV} = 90\ W/m^2 = 9\ mW/cm^2 , \tag{6}$$

From (5) and (6) results that the UV radiation (E_{UV}) is 5...10 % from the sun irradiance E.

Other natural sources of radiation containing UV spectra are: the moon (by the sunlight reflected), the stars, the sky, but they are very weak, compared with the UV sun radiation. There are also several artifcial UV sources, such as lamps (with xenon, mercury, zirconium, argon, etc) which can produce radiations, containing UV spectra. From the spectral distribution of 24.8 kW Vortex-stabilized Argon arc lamp results that the UV region represents 30%, that is 300W/sr. Considerring uniform spectral distribution, for a 1 m distance from the lamp it results an irradiation of 2.4 mW/cm^2. For a 10 m distance it results the value of irradiation is 0.0024 mW/cm^2. These considerations indicate different levels of UV rediation generated by the natural and artificial UV sources, which are important to establish the input range of UV radiation sensors. Due to the fact that these sources generate additional radiations (visible and IR) above UV it is necessary for UV sensors to exclude them.

From the Figs. 1-3 results that the UV spectra is a little part of the integral spectra of these sources. For the UV sensors it's necessary to exclude the visible and IR spectra.

2. PHYSICAL CONSIDERATIONS

Conversion efficiency and spectral sensibility of UV sensors are determined by many factors, the most important being the bandgap of utilized semiconductors. The most perspective materials for UV range are the semiconductors with bandgap $E_g > 2.5$ eV ($\lambda < 0.49$ μm), where:

$$E_g(\mathrm{eV}) = \frac{1.24}{\lambda(\mu\mathrm{m})}, \tag{7}$$

Moreover, it is strict necessary to consider the material reflection and refraction coefficients for $\lambda < 0.49$ μm, defect density in potential barrier region, condition of structure surface. Si, III-V compounds and related solid solutions, II-VI compounds, SiC, etc. are used now for UV sensors fabrication. UV sensors have to possess a high separation efficiency of charge carriers, generated by UV radiation at structure surface. So a low density of energetical states at surface and a presence of superficial potential barrier are required. The structures on p-n junction, Schottky barrier and heterostructures with optical window are the most widespread. Since Si is the most used semiconductor, sensors on the basis of single-crystal Si with surface p-n junction (depth ~ 0.1 μm) and on the basis of MOS structures were realized. But in both cases the photosensibility maximum is placed in near IR spectral region[2-4]. More efficient are the structures with Schottky barrier on Au-GaAs [5]. Photosensibility spectrum of these structures has maximum for photons hν ≈ 2.5 eV and an external efficiency of 40% in photosensibility maximum. Using Au - $nGaAs_{0.6}P_{0.4}$ structures an efficiency of 40% for photons hν = 3.5 eV (λ = 0.36 μm) was obtained[6]. $Ga_{1-x}Al_xP$ ternary compounds allow to extend the photosensibility up to 3.1 eV. The quantum efficiency of Au - $nGa_{1-x}Al_xP$ - nGaP structures is 30%[7]. UV sensors on SiC are also intensive elaborated. Bandgap of this material varies in interval 2.3 eV (β-SiC) ÷ 3.3 eV (2H-SiC). UV sensor on SiC, realized on the basis of epitaxial p-n junction, has maximum sensibility for λ = 0.27 μm and monochromatic efficiency 70%[8]. Efficient UV sensors were made on n(p)GaP - SnO_2 heterostructures. They have a high conversion efficiency in impulse regime (50-60 %) and a simple manufacturing technology. But all UV sensors, made on semiconductors with bandgap less than 3.1 eV, are sensible also to visible radiation. Sensors, made on wide bandgap semiconductors (SiC, diamond), have a complicate manufacturing technology of potential barrier.

To exclude the influence of visible radiation in UV sensor photocurrent, we have proposed and realized a structure of differential sensor on the basis of single-crystal Si.

3. STRUCTURE, CHARACTERISTICS AND PARAMETERS

A new structure of sensor, proposed by us for patent[9], permits to exclude this influence (Fig. 2). The sensor can be of several types: p-n junction, MOS or Schottky stuctures, photoresistor, etc. The sensor active surface is devided in two identical photocells. One cell is covered with a layer (6), transparent for visible and IR radiation and completely non-transparent for UV radiation. The photocells are differentially connected to a loading resistor (7).

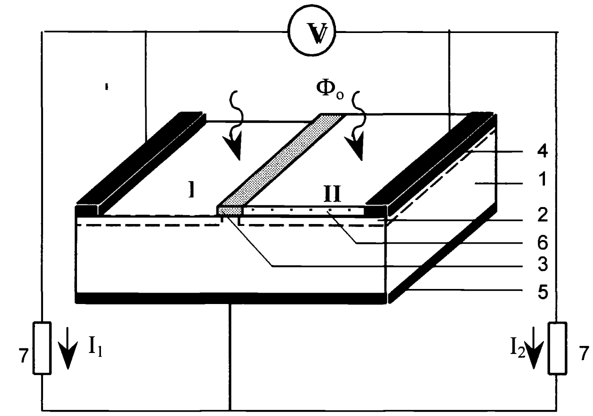

Fig. 4 Differential UV radiation sensor

1 - p-region; 2 - n-region; 3 - SiO_2 layer; 4 - front metal contacts; 5 - rear metal contact; 6 - ZnS layer; 7 - loading resistor.

The photocurrent of first cell I_1 is formed by total spectrum of incident light flux and the photocurrent of second cell I_2 is formed by IR-visible component of solar radiation. Differential connection of sensor cells to the load excludes from photorespond the visible and IR components, which are common for both cells. In result, the photorespond will be proportional with UV radiation intensity.

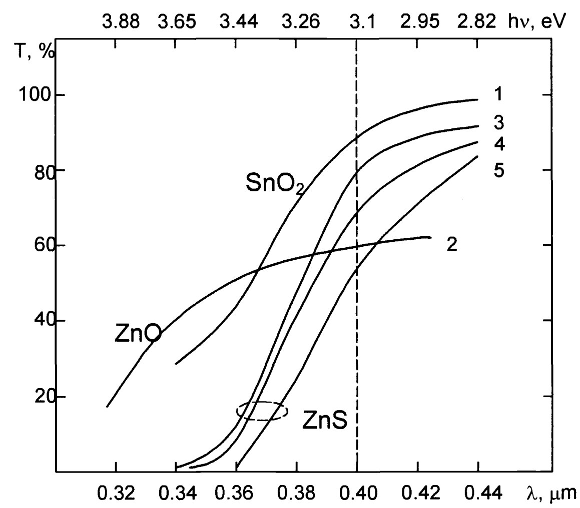

Fig. 3 Light transmission spectra of glass-semiconductor structures
1 - glass-SnO_2; 2 - glass-ZnO (1 μm); 3 - glass-ZnS (0.43 μm); 4 - glass-ZnS (0.76 μm); 5 - glass-ZnS (1 μm)

This UV sensor can be manufactured on cheap semiconductor materials, such as silicon, its structure is very simple and it can be sensible in the whole light spectrum. It simplifies the sensor manufacturing technology and diminish its cost.

To demonstrate the work ability of differential UV sensor, a photosensible structure on single-crystal Si wafer was produced. The p-n junction with depth 0.2 μm was obtained by diffusion of P in Si wafer. Both active front surfaces were separated by photoetching method and the structures were passivated by electrolytic anodization. Al+Ni metal contacts were formed by vacuum deposition.

To select an optimum material for layer 3 (Fig. 2), which is non-transparent in visible and IR spectral regions, the SnO_2, ZnO and ZnS thin films were investigated. These films were deposited on thin glass plates by vacuum and pyrolysis methods. Fig. 3 shows the light transmission spectra of these structures.

It is clear (Fig. 3), that the most suitable films are ZnS ones with thickness ~ 1 μm. They are transparent for radiation with wavelength $\lambda > 0.45$ μm and, practically, absorb all UV radiation with $\lambda < 0.36$ μm. Moreover, ZnS films are formed by vacuum deposition, that allows to reproduce very exactly the film thickness. Because it is practically impossible to obtain two photocells with same voltage-current characteristics and to exclude the influence of violet component from absorbed radiation ($0.4 < \lambda < 0.45$ μm), which is at the level ~ 20% (Fig. 3, curve 5), a special measuring system was used (Fig. 4).

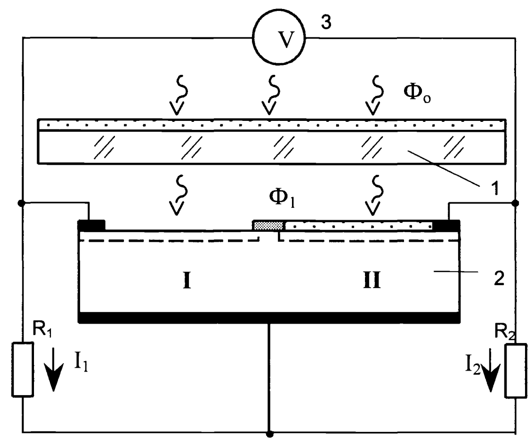

Fig. 4 Measuring scheme of differential UV sensor
1 - glass plate with ZnS layer, 2 - differential sensor, 3 - millivoltmeter, R_1 , R_2 - loading resistors

The UV sensor, differentially conected, has been covered with a glass plate, containing a 1 μm ZnS layer. The destination of such filter consists in excluding of UV spectrum component from incident light flux Φ_o. Also, the 20% part of violet radiation is cut from flux Φ_o (Fig. 3). The light flux Φ_1, penetrating the glass filter, is equally absorbed by both cells of sensor. The variable loading resistors R_1 and R_2 allow to equalize the difference between the currents I_1 and I_2, caused by disaccord of sensor photocells. In this case, the differential signal registered by millivoltmeter 3 is equal to zero. When the glass plate is removed, the sensor cells have different photocurrents. The photocurrent I_1 will be proportional to whole spectrum of incident flux Φ_o, while the photocurrent I_2 - to spectrum of flux Φ_1, limited by fundamental absorption threshold of ZnS. Fig. 5 shows the spectrum distribution of sensor cell photorespond. One can see that the differential signal is formed by difference between cell photocurrents (shaded region in Fig. 5).

As the curve of ZnS film light transmission (Fig. 3) has not an absolutely vertical steep, not all UV radiation is fixed in differential signal. About 20% of photons with $0.36 < \lambda < 0.4$ μm are received by both cells and do not contribute to differential signal formation. Also 20% of visible domain photons $0.4 < \lambda < 0.45$ μm can not be received by cell II, covered with ZnS, but they can be received by cell I (without ZnS) and compensate the lost part of UV radiation. Thus, we can affirm that differential photosignal of proposed sensor is proportional only to UV radiation intensity of incident light flux. The absolute value of differential signal depends on area of sensor photoactive surface. The photoactive surface area of each cell of realized sensor was $S = 0.84$ cm^2. The power of incident flux was $\Phi_o = 80$ mW/cm^2. The differential signal was $U_{dif} \approx 1$ mV for loading resistor $2 \times 100\ \Omega$. The spectrum sensibility changed in interval $S_{\lambda=0.4} = 0.101$ A/W and $S_{\lambda=0.34} = 0.031$ A/W.

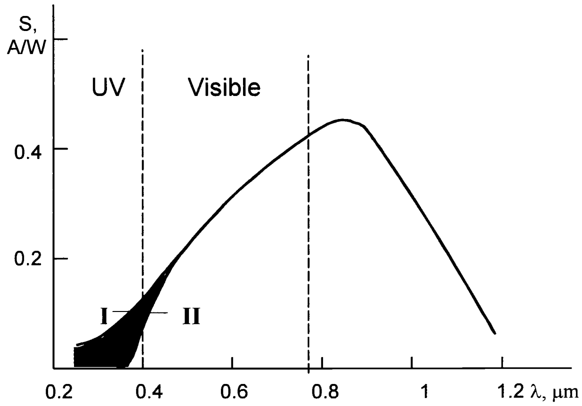

Fig. 5 Spectral distribution of cell photoresponds of UV sensor

4. CONCLUSIONS

To exclude completely the influence of visible radiation in photorespond forming, a new construction of sensor was elaborated and manufactured on Si. The peculiarity of this sensor consists in differential connection of two photoactive cells, having some sensibility in UV region, on one of which a layer non-transparent for UV radiation is formed. This sensor can be made on the basis of semiconductor materials with bandgap smaller than energetic threshold between UV and visible regions. This fact simplifies considerable the manufacturing technology of UV radiation sensor and diminish its cost.

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