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UV-sensitive optical sensors based on ITO-gallium phosphide hetero-junctions

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Design and characteristics of wide-band UV sensors based on ITO/GaP heterostructures are discussed. Such sensors have perfect electrical parameters and high UV-visible sensitivity in comparison with surface-barrier structures using a semi-transparent thin metal film as an electrode. Many applications require UV sensors with an effective rejection of visible radiation and a wide temperature operating interval. For this aim, the theoretical modelling of extreme selective optical sensors with a double Ag/ITO thin film on the GaP surface, in which the thin silver film serves as a narrow bandpass filter at 320 nm, has been conducted. With this modelling the optimal thickness combination for the silver and ITO films was found for the maximum rejection of the sensitivity to visible radiation.

1 Introduction Surface-barrier photodetectors based on wide energy gap GaP are extremely attractive for ultraviolet (UV) instrumentation due to high detectivity and production simplicity, and wide temperature operating rate. The junction can be formed by deposition of a semi-transparent metal or transparent conductive oxide (TCO) such as microcrystalline tin-doped indium film (ITO) onto the etched semiconductor surface. High-sensitivity (ITO)/GaP heterojunction UV-visible photodetectors have already been demonstrated as an alternative to the conventional Schottky photodiodes with semi-transparent gold electrode [1]. Performance of these optical sensors depends on the various factors such as optical and electrical properties of the front electrode, its thickness as well as the semiconductor substrate characteristics. UV narrow band optical sensors are important for different medical and technical applications. One of those is UV flame detectors for combustion systems. In gas burners the relative intensity of flame radiation is dominant in the UV region. In the visible and IR regions the relative intensity of radiation of the incandescent surfaces is several orders of magnitude greater than the gas flame radiation intensity. Therefore it is required that the flame detector has a much greater sensitivity in the UV region. Figure 1 from [2] well illustrates these requirements on example of two industrial sensors.

The selective UV surface-barrier sensors with perfect electrical characteristics have been analyzed in [3]. This selectivity was obtained thanks to the appropriate choice of a silver (Ag) film as the gate material. Such film presents a narrow band transmission at 320 nm due to the plasma resonance effect. However, the sensors reported here were not optimized for the rejection of visible radiation.

In this paper we discuss a new selective UV sensor based on a two layered Ag/ITO thin film on n-n$^+$ GaP epitaxial structures, in which the ITO film forms a heterojunction with the GaP, and the silver film serves as a narrow UV bandpass filter. The theoretical analysis of the performance of such sensors is the second objective of our work.

Because the rejection of the sensors sensitivity in the visible and near infrared spectral ranges depends on the optical constants of the interface materials, the optimal combination of thicknesses for the Ag and ITO films was found using theoretical calculations.

Contributed Article

It is clear the importance of the sensors selectivity to be insensitive to the blackbody radiation in a combustor.

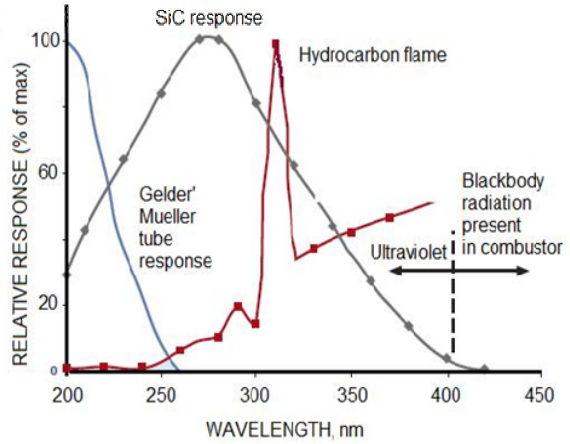

Figure 1 The spectral sensitivity of industrial SiC sensor together with Geller´ Mueller tube and the emission of hydrocarbon flame in gas turbine combustors [2].

2 Device design and performance Figure 2 shows the schematic cross section of the heterostructure. Monocrystalline n-n$^+$ GaP substrates with thicknesses of the epitaxial layers of 10-12 µm were used for device fabrication. The estimated electron density in the epitaxial layer was of the order of 10^{16} cm^{-3}. The back Ohmic contact was formed by indium diffusion. A sputtered SiO_x layer with thickness of 150 nm was used to passivate the non-active area of the front surface. Different deposition techniques were tested to produce the transparent electrode.

High quality microcrystalline ITO layers have been deposited by magnetron sputtering in the presence of an argon atmosphere [1]. The silver film was deposited by thermal vacuum deposition technique. Thicknesses of the Ag and ITO films have been used accordingly to results of optimization of the sensors selectivity obtained by calculations (the next chapter).

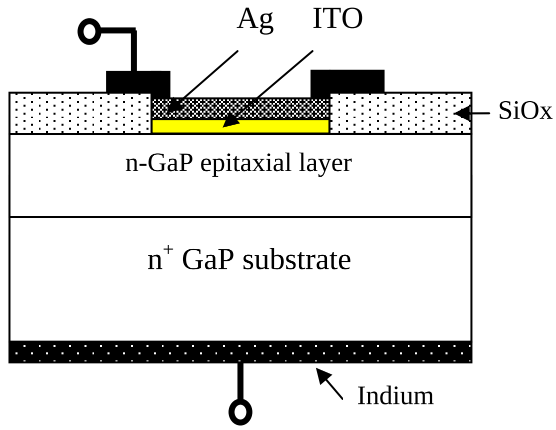

Figure 2 Schematic cross section of the Ag/ITO/n-n$^+$ GaP optical sensor.

2.1 Electric and photoelectric properties of ITO/n-n$^+$ Gap sensors The typical performance parameters of the photodiodes with ITO layer thickness of 65 nm are summarized in Table 1.

Table 1 The typical performance parameters of the photodiodes with ITO layer thickness of 65 nm.

Window electrode material	ITO
Active Area (mm^2)	3
Terminal Capacitance (nF)	1.5
Dark Current at V_R=1 V (pA)	~10
Shunt Resistance (GΩ)	30
Peak sensitivity wavelength (nm)	435
Responsivity (A/W)	0.20-0.32
NEP (W/Hz$^{1/2}$)	~$1 \cdot 10^{-15}$

The spectral response characteristics of the sensors with various ITO film thicknesses are shown in Fig. 3. The spectral response depends on the thickness of the ITO film.

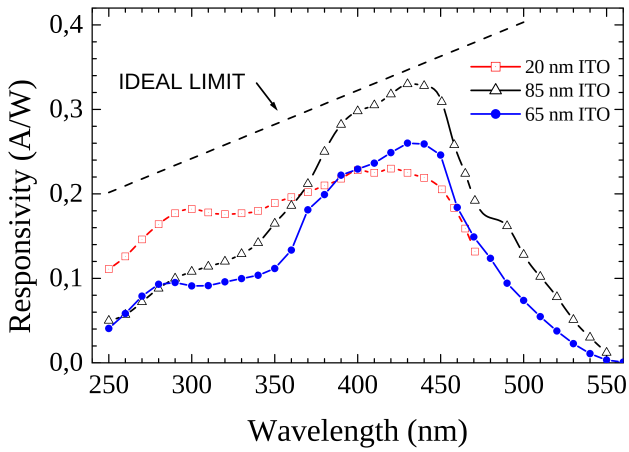

Figure 3 The spectral response characteristics of the ITO/n-n$^+$ GaP sensors with various ITO film thicknesses.

2.2 Modelling of optical properties of ITO/n-n$^+$ Gap sensors One of the key factors that determine the quantum efficiency of the surface-barrier ITO-GaP photodiodes is the optical property of the device interface. We consider an idealized interface, i.e., a uniform ITO film on the flat semi-infinite GaP substrate. The transmittance (T) of radiation at normal incidence through the ITO film into the GaP as a function of wavelength is computed from the next set of equations [4]:

$$T = \frac{n_2[(1+g_1)^2 + h_1^2][(1+g_2)^2 + h_2^2]}{exp(\beta) + (g_1^2 + h_1^2)(g_2^2 + h_2^2)\exp(-\beta) + 2Y},$$

$$g_1 = \frac{1 - n_1^2 - k_1^2}{(1+n_1)^2 + k_1^2}, \quad g_2 = \frac{n_1^2 - n_2^2 + k_1^2 - k_2^2}{(n_1+n_2)^2 + (k_1+k_2)^2},$$

$$h_1 = \frac{2k_1}{(1+n_1)^2 + k_1^2}, \quad h_2 = \frac{2n_1k_2 - 2n_2k_1}{(n_1+n_2)^2 + (k_1+k_2)^2}, \qquad (1)$$

$$\beta = \frac{4\pi \cdot n_1 d}{\lambda},$$

$$Y = (g_1g_2 - h_1h_2)\cos(\beta) + (g_1h_2 - g_2h_1)\sin(\beta),$$

were d is the ITO film thickness; n_1, k_1 and n_2, k_2 are the refractive index and the extinction coefficient of the ITO film and the GaP substrate, respectively. The published set of the optical constants for GaP and ITO [5] were used to perform this calculation.

Figure 4 shows computed transmittance at normal incidence as a function of wavelength for the ITO and Au film (for comparison) on GaP substrate.

A simple analytical model has been applied to calculate the internal quantum efficiency η_{int} of the ITO/ n-n$^+$-GaP structures. It was assumed, the first, that the recombination

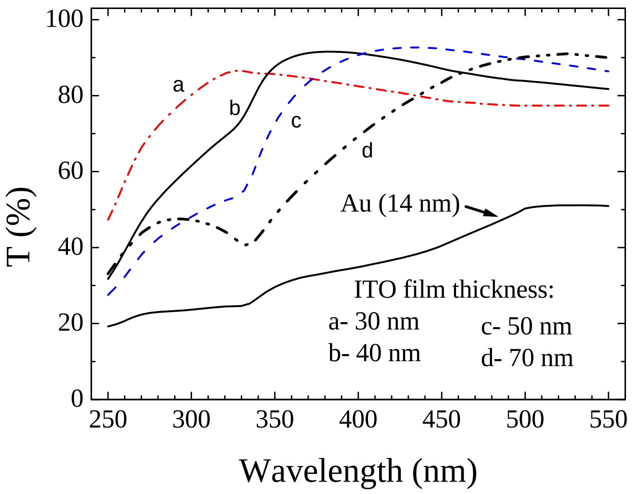

Figure 4 Computed transmittance at normal incidence as a function of wavelength for the ITO and Au film (for comparison) on GaP substrate.

losses at the heterojunction interface are insignificant. Secondly, we supposed that the contribution of photo-generated holes from the n$^+$-type substrate to the total photocurrent is negligibly small.

Under these conditions, and taking into account that the calculated value of T shown in Fig. 4 characterizes the photon flow penetrating the GaP substrate, the well-known simplified equation for external quantum efficiency η, for the case (1-R)=T where R is the reflectance from the sensor surface, is written as

In order to improve our estimations, in this work we used a more accurate equation from [6] to calculate the spectral characteristics for the quantum efficiency:

$$\eta = T\eta_{int} = T\left[1 - \frac{exp(-\alpha W)}{1+\alpha L_p}\right]$$

$$\eta = T\eta_{int} = T\left[1 - exp(-\alpha W)\cdot\left[1 - \frac{1-z}{1-(\alpha L_p)^{-2}}\right]\right], \qquad (2)$$

$$z = \frac{\frac{S}{\alpha D_p}\left[ch\left(\frac{y}{L_p}\right) - exp(-\alpha y)\right] + \frac{1}{\alpha L_p} sh\left(\frac{y}{L_p}\right) + exp(-\alpha y)}{\frac{SL_p}{D_p} sh\left(\frac{y}{L_p}\right) + ch\left(\frac{y}{L_p}\right)}$$

$$y = d - W, \quad W\left(\frac{2\varepsilon_s(V + V_{bi} - kT/q)}{qN_D}\right)^{1/2}$$

where η_{int} is the internal quantum efficiency, α is the absorption coefficient, S is the recombination velocity at the n-n$^+$ junction, ε_s is the permittivity of GaP, N_D is the donor concentration, V_{bi} is the built-in potential, V is the bias voltage, q is the electronic charge, constant D_p and L_p are the hole diffusion coefficient and diffusion length in the epitaxial layer, respectively.

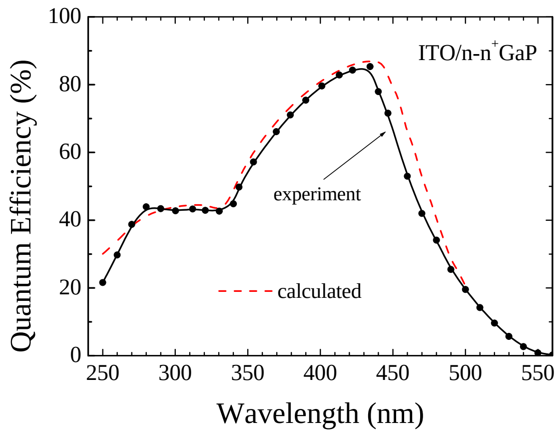

Figure 5 External quantum efficiency, calculated with Eq. (2) and that obtained experimentally, of the ITO/n-n+ GaP optical sensor with a 60 nm ITO film. The donor concentration, thickness of the epitaxial n-layer, and hole diffusion length are 10^{16} cm^{-3}, 12 μm and 3 μm, respectively.

Figure 5 shows that the long wavelength part of the spectral photoresponse is sensitive to L_p, while the sensor sensitivity in the UV spectral region is limited by the transmittance of the device interface and the external quantum efficiency with sufficient accuracy is equal the calculated transparency ($\eta = T$) due to the very high absorption coefficient (~ 10^6 cm^{-1}) and a negligible contribution from the diffusion.

2.3 Modelling of optical properties of Ag/ITO/n-n+ GaP sensors Silver is unique metal having a plasma resonance exclusive in UVA region of spectra. This feature has been used in this work for designing narrow band selective UV optical sensors. The position of the plasma resonance in Ag films is 320 nm. At this wavelength, the optical constants of silver change drastically, the reflection coefficient decreases to low value, and transmittance of UV radiation nearly 320 nm takes the place. The value of transmittance depends on the thickness of thin Ag film. It was found experimentally that decreasing the film thickness leads to bigger quantum efficiency of narrow-band Ag/ITO/n-n^+ GaP sensors at 320 nm, yet making worse a rejection of the sensitivity in visible and near infrared ranges. To optimize the quantum efficiency and rejection factor (ratio of the sensor sensitivity at maximum to the sensitivity in visible and near infrared range), the spectral dependence of transmission of two-layered Ag/ITO films onto GaP was simulated for varies combinations of thicknesses of these films. For the simulation, the transmission coefficient has been calculated in the spectral range 250-1000 nm using equation for two-layered (Ag/ITO in our case) structures [4] and tabulated spectral values of the optical constants of Ag, ITO, and GaP [5].

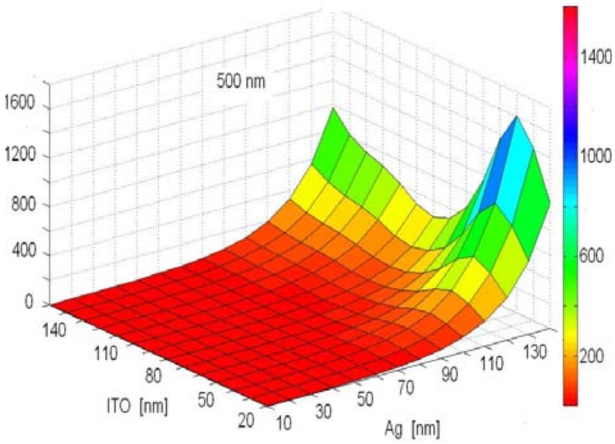

Figure 6 Rejection factors calculated for wavelength 500 nm at different thicknesses of ITO and Ag films on GaP.

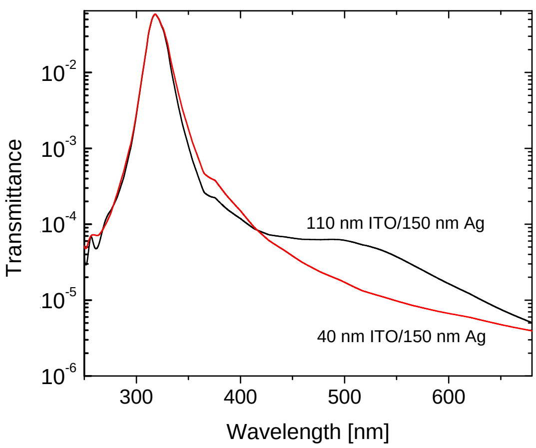

Figure 7 Calculated transmittance for two combinations of the film thicknesses on GaP.

Figure 6 shows the rejection factors calculated for wavelength 500 nm at different thicknesses of ITO and Ag films on GaP. Calculated transmittance for two combinations of the film thicknesses is shown in Fig. 7. From Fig. 8 it is possible to see the transmittance at 320 nm and the rejection factor for 400 and 500 nm at different Ag film thicknesses.

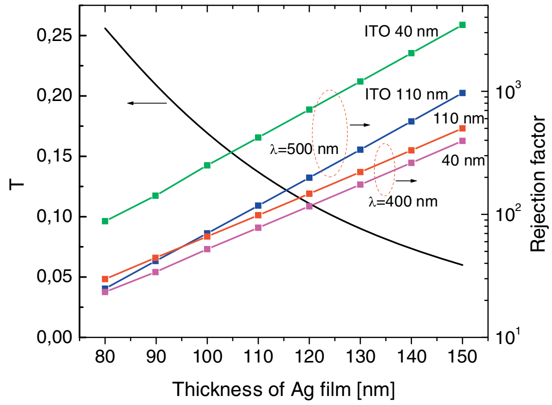

Figure 8 Calculated transmittance *T* at 320 nm and the rejection factor for 400 and 500 nm for the Ag film thickness.

The combination of 40 nm ITO film and 150 nm Ag film leads to a big decreasing of the transmittance (10^3 times) in comparison with transmittance at 320 nm. The half-wide band of the transmittance shown in Fig. 7 is 16 nm; the expected value of the external quantum efficiency is 0.06.

3 Conclusions We presented the perfect characteristics of simple to fabricate wide-band UV optical sensors based on ITO/n-n^+ GaP heterojunctions. The experimentally obtained external quantum efficiency agrees with the modelled one, which was based on the calculation of the light that penetrates through the Ag/ITO/GaP interfaces. The theoretical modelling also shows that narrow-band optical sensor for UVA range can be designed based on two-layered Ag/ITO/n-n^+ GaP structures. We found the optimal thickness combination of the Ag and ITO films for rejection of the sensitivity in the 400–500 nm spectral range.

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