Selectivity control of photosensitive structures based on gallium arsenide phosphide solid solutions by changing the rate of surface recombination

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Abstract. In this paper, we demonstrate the effect of surface recombination on spectral sensitivity of structures based on gallium arsenide phosphide solid solutions. Simulation of the effect for structures based on a p-n junction and a Schottky barrier was carried out. Photodetectors with different rates of surface recombination were fabricated by using different methods of preliminary treatment of the semiconductor surface. We experimentally demonstrated the possibility to control photodetector selectivity by altering the rate of surface recombination. The full width at half maximum was reduced by almost 4 times, while a relatively small decrease in sensitivity at the maximum was observed.

1. Introduction
Photosensitive structures and devices based on such structures are widely used in modern optoelectronics. An important characteristic of such structures and devices is the spectral sensitivity to photon flux radiation. Generally, the range is broad and greater than 300 nm. The benefit of such broadband photodetectors is versatility for recording signals from sources of various types. At the same time, the broadbandness is a drawback for some applications, because in addition to the desired signal, background signals from the Sun, illuminating lamps and other interference units can be recorded. To solve this problem, selective photodetectors with narrow spectral response should be employed [1], [2]. Besides, selective photodetectors should be capable of recording signals from a specified irradiator under strong background noise within other wavelength ranges. High selectivity can be achieved by using optical filters. Unfortunately, it is often the case that filters with necessary selectivity parameters cannot be found, or tend to degradation (solarization). Moreover, their implementation increases structural complexity, dimensions and device cost. Therefore, the optimum is to achieve the high selectivity by modifying operational principle of the photosensitive structures [3].

2. Experimental results and discussions
Surface and interface make significant contribution to operation of photosensitive structures due to a large number of defects and impurities, which appear as deep-level states in the band diagram, called surface states. In most cases, surface states have a negative impact on device operation, because their presence increases the recombination probability and as a consequence the photocurrent value decreases. However, it should be taken into account that contribution from surface recombination differs depending on sensitivity subranges, i.e. the difference in contribution is due to absorption
coefficient dependence of the photon energy. Thus, surface recombination is particularly evident in short-wavelength region of the spectral sensitivity.

In this work, we demonstrate the effect of surface recombination on spectral sensitivity of structures based on the p-n junction and the Schottky barrier. Based on solutions of the continuity equation we estimated the current flow through different parts of the structure and obtained expressions which describe transfer of photogenerated charge carriers. The calculations take into account effects of surface recombination on the illuminated side of the structure. Expressions for the quantum efficiency and the structure photosensitivity were obtained. Spectral sensitivity at various rates of surface recombination was calculated.

Consider an n-type semiconductor where electron-hole pair generation is caused by incident light with frequency \( h \nu \). The number of recombining minority carriers on the crystal surface per surface unit area is proportional to the deviation of the minority carrier concentration from the equilibrium value \([80]\). The distribution of the minority carrier concentration is given by the continuity equation.

Figure 1 shows the depth distribution of the generated carriers. The minority carrier concentration at the surface recombination rates \( s=0 \) cm/s and \( s=10^5 \) cm/s are marked by the solid and dashed curves correspondingly. The absorption coefficient is equal to \( 10^2 \) cm\(^{-1}\), the quantum efficiency is determined by the area under the curve.

**Figure 1.** The distribution of carriers generated in the sample

As shown in the Figure 1, when increasing the surface recombination rate the carrier concentration at \( x = 0 \) begins to fall, and the area under the curve as well as the quantum efficiency are reduced. However, at low values of the absorption coefficient the incident light deeply penetrates into the semiconductor layer, and a small fraction of carriers recombines on the surface. The more the absorption coefficient is, the more carriers are generated in the surficial region, the less carriers contribute to the photocurrent. Since \( \alpha \) increases with increasing the incident radiation energy (i.e. the illumination wavelength decreases), then we can control the photodetector sensitivity by varying the surface recombination rate in the short-wavelength range.

We have analysed two types of selective photodetectors based on A3B5 solid solutions. Figure 2 shows the result of calculation for a p-n junction with n-zone as a substrate.
The quantum efficiency as a function of the absorption coefficient (a) and the incident light wavelength (b) for a p-n-junction to GaAs$_{0.7}$P$_{0.3}$ $L_a = L_p = w = 5 \cdot 10^{-4}$ cm; $d = 5 \cdot 10^{-5}$ cm:  
1 - $s = 0$ cm/s; 2 - $s = 10^3$ cm/s; 3 - $s = 10^4$ cm/s; 4 - $s = 10^5$ cm/s; 5 - $s = 10^7$ cm/s.

Figure 3 shows the result of calculation for the metal-semiconductor contact illuminated from the metal film side. While the quantum efficiency significantly reduces at larger absorption coefficients, it remains almost unchanged at the maximum. At $\alpha = 10^5$ cm$^{-1}$ the sensitivity decreases by almost an order of magnitude, whereas at the maximum it remains at the level of 80% of the quantum efficiency at $s = 0$ cm/s.
The quantum efficiency as a function of the absorption coefficient (a) and the incident light wavelength (b) for a p-n-junction to GaAs$_{0.7}$P$_{0.3}$ $L_n = L_p = w = 5 \times 10^{-4}$ cm; $d = 5 \times 10^{-5}$ cm: 1 - $s = 0$ cm/c; 2 - $s = 10^3$ cm/c; 3 - $s = 10^4$ cm/c; 4 - $s = 10^5$ cm/c; 5 - $s = 10^7$ cm/c.

The calculations demonstrate the significant difference between the surface recombination effects on the sensitivity at the maximum and in the short-wavelength range. In general, the increase of surface recombination rate decreases the sensitivity in the photodetector operating range. Nevertheless, while the decrease at the maximum is relatively small and equal to 20-50 % depending on the structure type at high rates of surface recombination, the sensitivity decreases by 2-3 orders of magnitude in the short-wavelength range. Such effect can be used to achieve high selectivity without extra filtering (Figure 4).
3. Conclusion

The rate of surface recombination can be set by proper choice of preliminary treatment of the semiconductor surface. For this purpose, various etching reagents such as acids (hydrochloric acid, nitric acid, aqua regia etc.), alkali (KOH etc.) and their combinations with other reagents were used. Samples treated with abovementioned methods as well as non-treated samples were fabricated. The structures were sensitive in the visible and ultraviolet spectrum ranges. While the long-wavelength edge was set by the solid solution composition and the Schottky barrier height, the short-wavelength edge was primarily dependent on the rate of surface recombination. The structures based on epitaxial gallium phosphide layers had the following parameters: responsivity of 0.19 A/W at the maximum, full width at half maximum (FWHM) of 200 nm, dark current of -0.02 pA at a reverse bias of V = -1 V. Surface treatment reduced FWHM by almost 4 times. At the same time, the sensitivity at the maximum was reduced by less than 50%, whereas in short-wavelength region the sensitivity decreases by almost two orders of magnitude. Currently, we work on further improving the selectivity and increasing the sensitivity of the photodetectors.

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