Calculation of Quantum Efficiency of Photodetectors Based on A3B5 Metal-Solid Solutions Contacts

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Abstract. In our investigation, we have modelled the quantum efficiency of the photodetecting structures based on the p-n junction and metal-semiconductor contacts. The calculation has been performed based on the solution of the continuity equation, taking into account the impact of the surface recombination. In most cases, this process has an adverse effect on the parameters of instruments; in particular, in photodetectors, this effect should reduce sensitivity. However, in our investigation it is shown that the effect of the surface recombination may be used as a useful factor for developing selective photodetectors. The effect of the surface recombination process will significantly increase with an increase of the absorption coefficient, since in this case more photons will be absorbed at the surface. Since there is a significant dependence of the absorption coefficient on the incident photon energy in semiconductors, the effect of the surface recombination on the photodetector sensitivity in the long-wave and short-wave regions of the spectral range will be significantly different.

1. Introduction

Photodetectors based on metal-semiconductor contacts are widely used in modern electronics. Such devices offer high sensitivity and enhanced response rate [1]. Furthermore, relatively simple methods of the vacuum deposition of the metal layers are used in their creation, which has a beneficial effect on their cost. The key characteristics of photodetectors are their quantum efficiency and spectral characteristics of sensitivity [2]. In many cases, the calculations of these characteristics are limited to consideration of dependence of the absorption coefficient for a semiconductor. At the same time, in case of the structures based on metal-semiconductor contact, it is necessary to consider a number of additional factors, in particular, the surface condition, the above-barrier transport processes, et cetera [3].

Consideration of the processes of the surface recombination has been a specific feature of the modelling performed. The surface recombination is understood as a dramatic increase in the probability of the electron-hole interaction processes caused by the presence of a higher concentration of defects at the outer boundary of a semiconductor crystal or near the heterointerfaces inside the multilayer structure. In most cases, this process has an adverse effect on the parameters of devices. In field effect transistors, the effect of the surface recombination leads to a decrease in the amount of the
charge carriers passing through the channel, which deteriorates the transfer coefficients and other characteristics of a device. In photodetectors, this effect should reduce photoresponse, since the electron-hole pairs generated by a flux of photons will recombine near the surface of a semiconductor until they reach ohmic contacts. Nevertheless, in our investigation it is shown that the effect of the surface recombination may be used as a useful factor enabling photodetectors with selective spectral characteristics, without using external optical filters. In this case, sensitivity in the spectrum maximum $S_{\text{max}}$ slightly decreases with a decrease of the spectral characteristics width in the half maximum up to the values of $\Delta \lambda_{0.5} = 40$ nm or less. Development of selective photodiodes is one of the main challenges of modern optics [4]. The use of such effects is relevant to develop solar-blind and visible-blind photodiodes [5, 6].

2. Experimental results and discussions

Let us consider the photodetective structure based on the p-n-junction. Let this structure be illuminated from the side of the p-region by a flux of photons $\Phi_0$ with energy $\hbar \omega$ that is greater or equal to the band gap width of a semiconductor $E_g$. Let us take the p-region thickness of width $d$ as large enough for surface defects not to affect the processes in the space charge region of width $w$. In this structure, the incident light will give rise to generation of the electron-hole pairs practically in the full depth thereof. In this case, the coordinate $x$ corresponding to the geometric position of the photon absorption point will be determined by the Bouguer-Lambert Law, whereby the radiation intensity will decrease exponentially with the passing of light through a semiconductor. The concentration of the nonequilibrium charge carriers in the structure will change in a similar way. We can calculate the distribution of this concentration based on the solution of the continuity equation. In the case under consideration, this solution becomes:

$$n_p(x) = n_{p0} + \tau_n \left(1 - e^{-x/L_n} s \tau_n \frac{L_n}{L_n + s \tau_n}\right) \Phi_0 e^{-\alpha x},$$

where $\tau_n$ and $L_n$ are the lifetime and diffusion length for the minority charge carriers; in this case, for the electrons in the p-region.

The key factors that determine the distribution of the generated carriers in the structure depth are the absorption coefficient $\alpha$ and the surface recombination rate $s$. Let us consider the distribution for the case of a thick p-layer ($d > 0.1$ mm). It is obvious that with an increase of the absorption coefficient, the depth of the light penetration decreases. This means that for small values of $\alpha$, the light will pass deep into the structure, while for large values of $\alpha$, almost all the photons will be absorbed at the very surface.

If there is significant surface recombination ($s > 10^5$ m/s), the concentration of the nonequilibrium carriers at the semiconductor surface will decrease. However, the impact of this effect for the curve with the large absorption coefficient will be much higher, since in this case much more carriers will emerge at the very surface. The quantum yield of such a photodetector, and, hence, its sensitivity will generally correspond to the areas under the curves. In semiconductors, there is a significant dependence of the absorption coefficient on the incident photon energy, which is particularly evident near the absorption edge. This makes it possible to talk about the different impact of the surface recombination rate on the photodetector sensitivity in the long-wave and short-wave regions of the spectral range.
To verify this fact, we have modelled the effect of the absorption coefficient on the quantum yield of a photodetector considering the effect of the surface recombination. The modelling was based on the solution of the continuity equation for the p- and n-regions, as well as for the space-charge region. Let us consider each of these regions in more detail.

P-region. The concentration of the photogenerated minority charge carriers for the p-region may be determined from the following equation

\[ \frac{d^2 (\Delta n)}{dx^2} - \frac{\Delta n}{L_p^2} = - \frac{q\Phi_0 \cdot \alpha \exp(-\alpha x)}{D_n}. \]  

In our investigation, boundary conditions were determined in such a way as to take account of the effect of the surface recombination on the current transport processes in the photodetector structures:

\[ s \cdot \Delta n \bigg|_{x=0} = D_n \frac{d(\Delta n)}{dx} \bigg|_{x=0}, \]

\[ \Delta n \bigg|_{x=w} = 0. \]  

Then the current density will be determined by the following expression

\[ J_{\phi,p,n} = q\Phi_0 \frac{\alpha L_n}{\alpha^2 L_n^2 - 1} \left[ \frac{\alpha L_p + \frac{L_n}{L_s} \cdot \exp\left(-\frac{L_n}{L_s}\right) \cdot \left( \frac{w}{L_n} \right) + s h\left( \frac{w}{L_n} \right)}{L_p \cdot \frac{L_n}{L_s} \cdot \exp\left(-\frac{L_n}{L_s}\right) + s h\left( \frac{w}{L_n} \right)} \right] - \alpha L_n e^{-\alpha w}. \]  

Here we have used a connection between the surface recombination rate and the diffusion coefficient

\[ s = \frac{D_n}{L_s}, \]  

that allowed to simplify the equation record.

Space-charge region. In this case, the photocurrent is determined by the generation in the region from the point \( w \) to the point \( d \)

\[ J_{\phi,p-n} = -q \int_{w}^{d} G(x) dx \]  

whereby we obtain the expression for the photocurrent density in the p-n-junction:

\[ J_{\phi,p-n} = q\Phi_0 \left[ \left[ 1 - \exp\left(-\alpha d \right) \right] \exp\left(-\alpha w \right) \right] \]  

N-region. The concentration of the photogenerated minority charge carriers for the n-region may be determined from the following equation

\[ \frac{d^2 (\Delta p)}{dx^2} - \frac{\Delta p}{L_p^2} = - \frac{q\Phi_0 \cdot \alpha \exp(-\alpha x)}{D_p}. \]  

with the use of boundary conditions

\[ \Delta p \bigg|_{x=w+d} = 0 \]

\[ \Delta p \bigg|_{x \to \infty} = 0 \]
Then the current density will be determined by the following expression

\[
J_{\Phi, p} = -qD_p \frac{d(\Delta p)}{dx} \bigg|_{x = w + d} = q\Phi_o \frac{\alpha L_p}{1 + \alpha L_p} e^{\exp[-(w + d)\alpha]}
\]

As it is known, the quantum efficiency of a photodiode may be determined from the value of the photocurrent arising when its sensitive area is illuminated by radiation of power \(P_{\text{opt}}\), according to the formula (1.3). Then dependence of the quantum efficiency on the absorption coefficient in the structure based on the p-n-junction may be calculated from the sum of the photocurrents specified above for the considered parts of the structure:

\[
\eta(\alpha) = e^{-\alpha w} (1 - e^{-\alpha d}) + \frac{\alpha L_p}{1 + \alpha L_p} e^{-(w+d)\alpha} + \frac{\alpha L_n}{\alpha^2 L_n^2 - 1} \left[ \frac{\alpha L_p + \frac{L_n}{L_s} - e^{-\alpha w} \left( \frac{L_n}{L_s} \text{ch} \left( \frac{w}{L_n} \right) + \text{sh} \left( \frac{w}{L_n} \right) \right) - \alpha L_n e^{-\alpha w}} \right]
\]

The results of the modelling of the spectral characteristics of the photosensitive structures based on the p-n-junctions at different surface recombination rates show that by increasing the absorption coefficient up to 100 cm\(^{-1}\), the quantum yield rapidly increase, and a change of the surface recombination rate has almost no effect on this increase. At the same time, with an increase of the absorption coefficient up to the values of \(\alpha = 10^5\) cm\(^{-1}\), an increase of the surface recombination rate leads to a decrease of the quantum efficiency by two orders of magnitude. It is important that sensitivity in the maximum of the spectral characteristics does not decrease so significantly (no more than by 20%).

The difference in a change of the quantum efficiency in various parts of the spectral characteristics is more evidently shown in Figure 1. It is seen that sensitivity in the maximum practically does not change, and short-wavelength sensitivity drops by almost 100 times.

Thus, modelling has shown that it is possible to achieve the selectivity effect in the structures based on the p-n-junctions by affecting the semiconductor surface and by changing the recombination processes occurring therein.
Figure 1. Dependence of the quantum yield on the surface recombination rate in the short-wave part of the spectral characteristics (1) and in its maximum (2) for a photodetector based on the p-n-junction.

We can increase the effect of the surface recombination on the characteristics of a photodetector in case we use a rectifying metal-semiconductor contact in the basis of the photodetector structure. Let us consider a device based on the Schottky barrier n-type metal-semiconductor. In this case, the structure is changed as follows: instead of the p-region, there will be the metal layer in the structure, which is in direct contact with the surface of the n-type semiconductor. In this case, the surface recombination will have an impact on the processes occurring in the space charge region, i.e. where effective separation of the electron-hole pairs should occur. However, at a relatively low dopant concentration in a semiconductor, the space charge region may be quite extensive, and there will be a difference between the effect of the surface recombination on the long-wave and short-wave parts of the spectral characteristics, which is similar with the structure based on the p-n-junction.

In order to test the hypotheses specified above we have modelled dependence of the quantum yield on the absorption coefficient in the structures based on the Schottky barrier. Illumination of the structure was carried through the upper metal contact. The thickness of the metal layer was taken as low enough to consider the metal film semi-transparent with the minimal absorption therein. In this case, the contribution of the effect of the above-barrier transport may be considered insignificant. The modelling was performed based on the solution of the continuity equation.

In the structures based on the Schottky barriers, it is convenient to consider the calculation of the current transport processes in terms of the drift component $J_{dr}$ and diffusion component $J_{dif}$ of the total current:

$$J_{total} = J_{dr} + J_{dif}$$

The diffusion current component is determined similarly to the current in the n-region of the structures based on the p-n-junction:

$$J_{dif} = q \Phi_0 \left( \frac{\alpha L_p}{1 + \alpha L_p} e^{-\alpha w} \right)$$

The drift current component is calculated from the equation that describes the photogeneration processes of the charge carriers in the space charge region. But in the case of the Schottky barriers, we should take into account the presence of the surface states at the metal-semiconductor boundary and the recombination related therewith:
\[ G(x) = \Phi_0 \alpha e^{-\alpha x} \left( 1 - \frac{S \tau}{L_p + \tau S} e^{-\frac{x}{L_p}} \right) \]  \hfill (14)

Then the drift current component may be determined from the following equation:

\[ J_{dr} = -q \int_0^w G(x) dx = q \Phi_0 \left( 1 - e^{-\alpha w} + \frac{S \tau}{L_p + \tau S} \frac{\alpha L_p}{1 + \alpha L_p} \left( e^{-\frac{w}{L_p}} - 1 \right) \right) \]  \hfill (15)

Then, summing the expressions for the drift and diffusion current, it is possible to determine the total current in the Schottky barriers:

\[ J_{total} = q \Phi_0 \left( 1 - e^{-\alpha w} + \frac{S \tau}{L_p + \tau S} \frac{\alpha L_p}{1 + \alpha L_p} e^{-\frac{w}{L_p}} - 1 + \frac{\alpha L_p}{1 + \alpha L_p} \left( e^{-\alpha w} \right) \right) \]  \hfill (16)

Then, we may determine dependence of the quantum efficiency on the absorption coefficient in the structure based on the Schottky barrier. Taking into account the effect of the surface recombination rate, the quantum efficiency in the structure based on the Schottky barrier is determined by the following expression:

\[ \eta = \left( 1 - e^{-\alpha w} + \frac{S \tau}{L_p + \tau S} \frac{\alpha L_p}{1 + \alpha L_p} e^{-\frac{w}{L_p}} - 1 + \frac{\alpha L_p}{1 + \alpha L_p} \left( e^{-\alpha w} \right) \right) \]  \hfill (17)

The results of the modelling of the spectral characteristics of the photosensitive structures based on the Schottky barriers at different surface recombination rates are generally similar to those for the structures based on the p-n-junction, but the effects described above are more evident. In particular, a drop of sensitivity increases both in the maximum and in the short-wave part of the spectral characteristics. However, sensitivity in the maximum decreases just by 1.5 - 2 times, while the short-wavelength sensitivity decreases by 2 orders of magnitude at the absorption coefficient of \( \alpha = 3 \cdot 10^4 \text{ cm}^{-1} \) and the half-width of the spectral characteristics at the same values of the surface recombination rate is significantly smaller.

When considering the results of the modelling, we should also consider that it is very difficult to get the surface recombination rates that are smaller than \( s = 10^5 \text{ m/s} \) in real structures. Therefore, a decrease of sensitivity in these structures should be counted from the specified curve. In this case, a drop of sensitivity in the maximum of the spectral characteristics is no longer seen as so significant (no more than 10 \%), while its decrease in the short-wavelength part of the spectrum still amounts to 50-100 times (Figure 2).
Figure 2. Dependence of the quantum yield on the surface recombination rate in the short-wave part of the spectral characteristics (1) and in its maximum (2) for a photodetector based on the p-n-junction.

Thus, it is shown that control of the surface recombination allows to change the sensitivity range of photodetectors.

3. Conclusion

It is established that when modelling the quantum efficiency of the photodetector structures based on the p-n junction and metal-semiconductor, it is necessary to take into account the effect of the surface states. It is shown that an increase in the surface recombination in the photodetector structures reduces the sensitivity range. In photodiodes based on the p-n-junction, at an increase of the absorption coefficient up to the values of $\alpha = 10^5$ cm$^{-1}$, an increase of the surface recombination rate leads to a decrease of the quantum efficiency by two orders of magnitude. It is important that sensitivity in the maximum of the spectral characteristics does not decrease so significantly (no more than by 20%). In photodiodes based on metal-solid solutions contacts, a drop of sensitivity increases both in the maximum and in the short-wave part of the spectral characteristics. However, photosensitivity in the maximum decreases just by 1.5 - 2 times, while the short-wavelength sensitivity decreases by 2 orders of magnitude at the absorption coefficient of $\alpha = 3 \cdot 10^4$ cm$^{-1}$, and the half-width of the spectral characteristics at the same values of the surface recombination rate is significantly smaller.

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