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doi:10.15199/48.2015.08.21

Controlling the characteristics of photovoltaic cells based on their own semiconductors

***Abstract**. The features of photovoltaic cells with their own photoconductivity in semiconductors with deep-level multiply-charge impurity have been considered. The use of such structures can significantly extend the dynamic range of sensitivity and gain new functional properties of single-element photoelectric receivers. Photovoltaic converters based on semiconductors with deep-level multiply-charge acceptor type impurity enable devices with a wider functionality, whereas the structure with multiply-charge donor type impurity has better linearity of energy performance. In the development of photoelectric receiver with advanced functionality features the model of recombination processes in multiply-charge impurity in a wide range of optical radiation power density has been used.*

***Streszczenie**. W pracy przedstawiono właściwości fotoelektrycznych przetworników z samoistną foto przewodnością na bazie półprzewodników z głęboką wieloładunkową domieszką. Wykorzystanie takich struktur pozwala w sposób istotny rozszerzyć zakres dynamicznej czułości i otrzymać nowe funkcjonalne właściwości fotodetektorów. Przetworniki fotoelektryczne na bazie półprzewodników z głęboką wieloładunkową domieszką typu akceptorowego pozwalją zbudować urządzenia o szerszej funkcjonalności, a struktury z wieloładunkową domieszką typu donorowego mają lepszą liniowość charakterystyki energetycznej. Przy projektowaniu foto odbiorników z rozszerzonymi funkcjonalnymi możliwościami wykorzystano model rekombinacyjnych procesów na wieloładunkowej domieszce w szerokiej skali gęstości mocy promieniowania optycznego. (**Kontrolowanie charakterystyk przetworników fotowoltaicznych w oparciu o półprzewodniki**)*

***Keywords:** photoelectric converter, switching characteristics, intrinsic conductivity, multiply charge impurity, charge state.*
***Slowa kluczowe:** przetwornik fotoelektryczny, przełączenia charakterystyk, konduktywność samoistna, wieloładunkowa domieszka, stan ładunkowy.*

Introduction

Photoelectric converters (PEC) based on semiconductors can be divided into two basic types: PEC-based semiconductors with the impurity conductivity and a relatively high impurity concentration (up to 10^{19} cm^{-3}), PEC-intrinsic based semiconductor materials containing residual multiply-charge impurities. The first type of photovoltaic devices is characterized by high sensitivity and saturation with the energy transfer characteristics at relatively low densities of optical power, which separates the dynamic range of PEC. The extension of linearity of energy performance up to radiation power density exceeding the threshold of saturation characteristics of the intrinsic and extrinsic photoelectric receiver through the use of control mechanisms of the charge state of deep-level impurity centers is possible in PEC with intrinsic conductivity [1, 2]. Moreover, controlling the PEC characteristics is possible due to saturation controlling of several levels of an impurity in a few charge states.

Statement of the Problem

Several photoelectric receiver structures with different parameters are usually used for applications requiring photoelectric receivers with variable characteristics, Such a composite photoelectric receiver requires additional optical elements and generally has a lower degree of sensitivity than each separate photoelectric receiver. However, this problem can be solved using one multifunctional single-element photoelectric receiver [3-6].

Photovoltaic converters with intrinsic photoconductivity in semiconductors with deep level multiply-charge impurity

The mechanism of controlling the charge state of multiply charge impurity centers in intrinsic semiconductors is recommendable to extend the functionality of single-element photoelectric receivers. This enables new options; controlling PEC characteristics with additional external interferences. Such a photoelectric receiver is performed in one volume with the intrinsic semiconductor, doped with deep multiply-charge levels. Another type of PEC intrinsic based semiconductors with deep level impurity is a structure with one or two counter included Schottky barriers (Fig.1). The structure of photoresistor PEC is shown On Figs.1a and 1b shows the diode structure of PEC with one Schottky barrier, Figure 1c shows the structure with two counter included Schottky barriers.

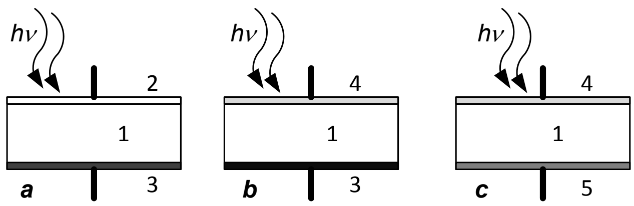

Fig.1. Photovoltaic converters with intrinsic photoconductivity based on semiconductors with deep level multiply-charge impurity. *1* – semiconductor with deep level multiply-charge impurity; *2* – semi-transparent ohmic contact; *3* – ohmic contact; *4* – semi-transparent Schottky barrier; *5* – Schottky barrier

At the same time the characteristics of PEC with a deep level impurity are determined by the nature of recombination processes through the levels of impurities in different charge states [1, 2]. Figure 2 shows the energy diagram of intrinsic germanium doped with Pt, forming three levels in the forbidden zone.

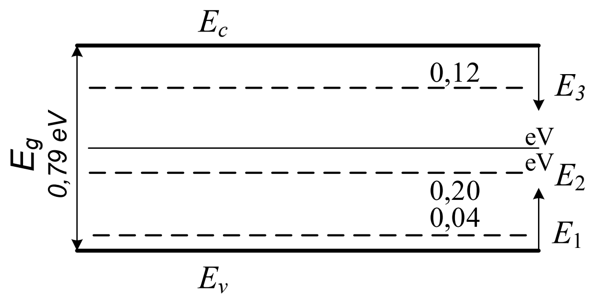

Fig.2. Energy diagram of self-Ge, doped Pt. E_1, E_2, E_3 – energy levels of platinum in charge states (-2, -1), (-3, -2), (-1, 0) eV

Simulation of PEC intrinsic based semiconductor characteristics with weekly doped with the multicharge impurity is carried out assuming that the PEC parameters are determined by the recombination processes in a wide range of optical radiation power density [2, 3].

The basis of the model [4, 5] is a system of kinetic equations describing the processes of recombination involving multiply charge impurities having any number of (i) levels in the band gap of the semiconductor:

$$N\gamma_{n,i-1}(F_{i-1}(n_0+\Delta n)-F_i n_{i-1}) = $$
$$= N\gamma_{p,i-1}(F_i(p_0+\Delta p)-F_{i-1}p_{i-1})$$
$$\Delta p = \Delta n + \sum_1 N(F_i - F_{i0}) \quad (1)$$
$$\sum_0 F_i = 1$$

where: N_i is the concentration of defects in the i - type, γ_{ni}, γ_{pi} are coefficients of recombination of electrons and holes in the defect i - type, n_0 is concentration of electrons in equilibrium, Δn is concentration of electrons in nonequilibrium, p_0 is concentration of holes in equilibrium, Δp is concentration of holes in nonequilibrium, n_i, p_i is density of states in c- and v-zones; f_i is stationary nonequilibrium function of filling defects of i-type.

In the case of recombination processes involving two multiply-charge impurity levels in the semiconductor band gap, such as (Ge (Cu)), being a system of kinetic equations of the model, is transformed into the following form

$$N\gamma_{n1}((n_0+\Delta n)F_1 - F_2 n_1) =$$
$$= N\gamma_{p1}((p_0+\Delta p)F_2 - F_1 p_1)$$
$$N\gamma_{n2}((n_0+\Delta n)F_2 - F_3 n_2) = \quad (2)$$
$$= N\gamma_{p2}((p_0+\Delta p)F_3 - F_2 p_2)$$
$$\Delta p = \Delta n + N(F_2 - F_{10}) + N(F_3 - F_{20})$$
$$F_1 + F_2 + F_3 = 1$$

The purpose of simulating is both the balance of impurity ions concentration in different charge states and the dependence of the development stages of primary and secondary charge carriers from the optical radiation power density:

$$\tau_n = \frac{\Delta n}{U_{n1}+U_{n2}} \qquad \tau_p = \frac{\Delta p}{U_{p1}+U_{p2}} \quad (3)$$

It is obvious that the system of equations of the model of the M types recombination centers (taken generally) cannot be solved analytically. To simulate the processes of recombination with arbitrary injection level in the case of any number of defects [7] the numerical method of calculation of stationary nonequilibrium functions of centers filling, their mutual influence with arbitrary injection level being taken into account, was suggested. In the stationary state the relation makes sense:

$$\sum_i^M (U_{ni} + \Delta U_{ni}) = \sum_i^M (U_{pi} + \Delta U_{pi}) \quad (4)$$

In this formula, U_{ni}, U_{pi} – is the total rate of capture of electrons and holes from the c to v zone respectively on the i-center in the absence of the remaining (i-1) centers; ΔU_{ni}, ΔU_{pi} is changing the rate of recombination of electrons and holes in the i-center due to the presence of other defects.

A method of calculation is described in [7] that allows to reduce the problem to a multi-level one-level by introducing an external self-consistent field.

Simulation results for the PEC with multiply charge impurities show that, depending on the stage of development of primary and secondary charge carriers from the optical radiation power density, there are two regions of linear recombination separated by the region of nonlinear recombination [3-6]. Figure 3 summarizes the PEC-based intrinsic semiconductor with deep multiply p-type impurities characteristic.

Automatic recharge of impurity levels in different charge states of deep level multiply charge impurities by increasing the power density of the optical signal which leads to the formation of two sub-bands of energy characteristics of the photoelectric receiver [3]. The first sub-band (region I) corresponds to a linear recombination at low optical power densities, less than a certain threshold value P_L, whereas the second sub-band linearity (region II) of energy performance is observed at high densities of large optical power P_H. If you change the optical power changes the concentration of impurity charge states with different ionization energies takes place, and automatic switching between the levels with a different degree of saturation corresponding to the optical radiation power. The result is an expansion of the dynamic range of the sensitivity of the photoelectric receiver.

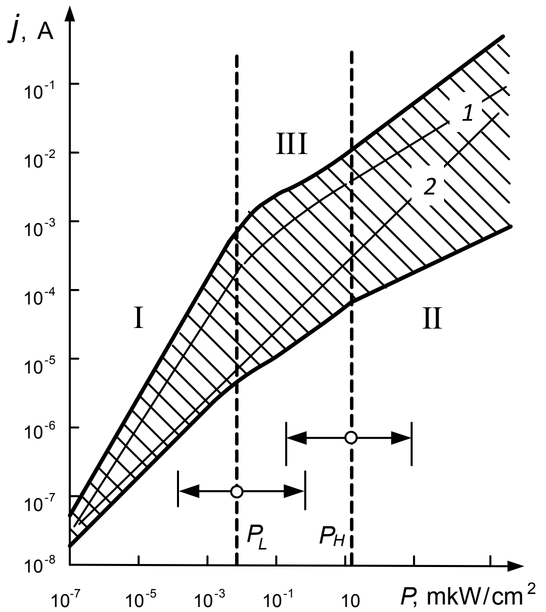

Fig.3. Generalized energy characteristics of germanium based PEC on (λ = 1.7 μm)

Greater expansion of dynamic range in the vicinity of the energy characteristics of PEC to the linear one can be achieved by introducing a deep level acceptor type impurity with three charge states, compared to that with two charge state impurities. At the same time, three regions of the linear dependence of energy characteristics are implemented, the regions being separated by two narrower regions with a nonlinear dependence.

Along with the transition from one region to another line changing high speed performance of photoelectric receiver based on the acceptor type semiconductor with multiply-charge impurity. Figure 4 shows the dependence of high speed performance of the photoresistant PEC, bound by the correlation between the constant and the the deep level recombination of the acceptor, determined by the level of arousal.

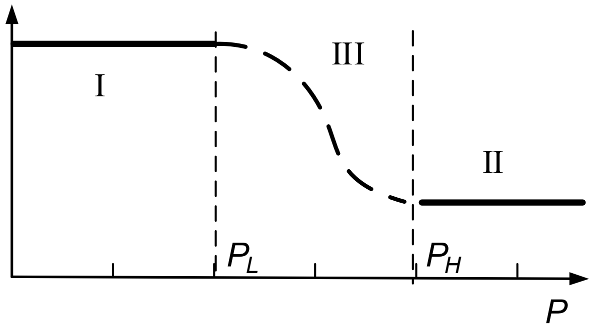

Fig.4. Correlation between the time constant of photoresistant PEC and the level of optical arousal

The specific type of energy characteristics of PEC [3] depends on the type of impurity and its concentration. PEC parameters in energy characteristics I and II can be controlled at the manufacturing stage photoelectric receiver structure and in a finished structure using, for example, additional interference [3-6]. Thus, the position of the boundaries of P_L and P_H can be synchronously changed into several decimal orders, the concentration of impurities being changed (Ge (Cu)) from 10^{12} to 10^{15} cm^{-3} [3]. The position of a specific energy PEC characteristic within the space of generalized characteristics (fig. 3.) depends on the type of a semiconductor material and impurity. Line 1 on Fig.3 corresponds to (Ge (Ni)). By varying the intensity of the radiation from the intrinsic absorption region the concentration of impurities in different charge states with different levels of ionization energy can be controlled. Depending upon the power density of the optical signal (of the additional intrinsic absorption or the main), various charge states multiply charge impurity and accordingly the spectral characteristics with a peak wavelength λ_1 or λ_2 are realized (fig. 5), the spectral characteristics being switched under the influence of radiation with the wavelength λ_0 [8].

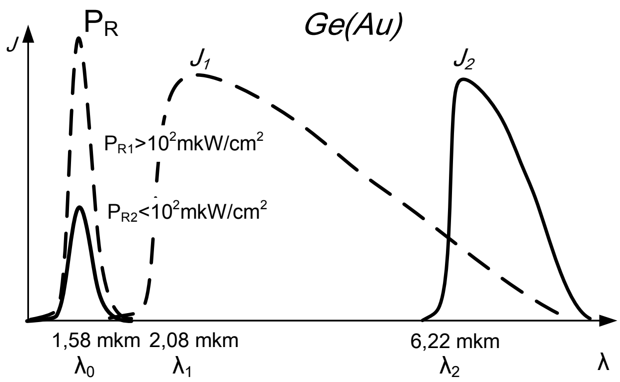

Fig.5. Switching the spectral characteristics of the photoelectric receiver with deep level multiply-charge impurity with additional illumination with a wavelength λ_0

The boundaries of the two sub-band linear of PEC power characteristics, PEC performance options in each of the sub-bands, the optical power density at which switching of the spectral sensitivity characteristics of PEC takes place, which enables numerical simulation of recombination processes in intrinsic semiconductors with multiply charge impurities. The developed model [4-6] allows you to define the characteristics of PEC being designed for a variety of impurities, forming an arbitrary number of levels in different charge states.

Another situation is different in the introduction to its intrinsic deep level semiconductor donor impurities [9], when the Fermi level is above the level of impurities (fig. 6) and the optical charge centers in different charge states occurs. Impurity centers is filled with electrons both at the low and high injection levels, the equilibrium Fermi-Dirac function is close to 1 and changes with the excitation level 10^{-3} (not higher) being increased, therefore, τ_n τ_p will not practically be affected by the injection level (fig. 7). This, in its turn, leads to the situation when there will be no energy characteristic nonlinearity between power levels P_L and P_H.

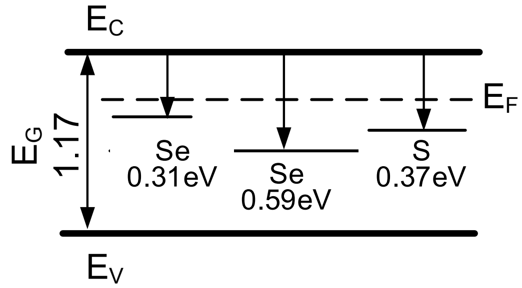

Fig.6. Energy impurity Se and S levels in Silicon at the temperature T=100 K.

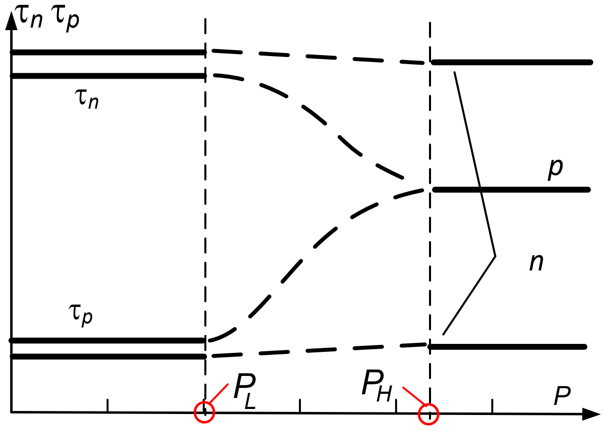

Fig.7. Dependence of the recombination time constant of deep level of acceptor and donor impurities on the excitation level

Thus, PEC donor type based semiconductors with deep level impurity will have a significantly better metrological characteristic [10] compared to PEC, doped by acceptor type impurity, but on the other hand, will not be able to implement switchable when changing the optical power density characteristics of PEC. More specifically, the appearance of an additional spectral range of sensitivity is observed for PEC with a donor impurity, but the intensity becoming that of 4-6 decimal orders of magnitude weaker than the values need for acceptor type impurity PEC.

At the temperature of about 100 K, energy performance of intrinsic semiconductor based PEC is linear with the deviation from linearity of less than 1%. Sensitivity is linear throughout the whole dynamic range and, more importantly, and the high speed performance of photoelectric receiver with a change in optical power is not changed.

At the temperature of about 300 K the impurity level is a bit higher than the Fermi level and is completely filled with holes. The equilibrium Fermi-Dirac function tends to a zero (about 10^{-4} - 10^{-5}) and at low levels of excitation of τ_n is substantially less of τ_p, and at high levels of excitation due to the growth of τ_n), an increase of the photocurrent (superlinearity) unlike deep p-type impurity PEC, wherein the second linear sub-band power characteristic slope is lower than at low excitation levels (sublinearity).

If you change the optical power (injection level) of τ_n and If you change the optical power (injection level) of τ_n and τ_p when doping an acceptor type impurity τ_n and τ_p vary by several decimal orders of magnitude. This leads to the fact that the when transferring to a different sub-band of power and spectral characteristics, high speed performance of photoelectric receiver with a deep multiply-charge acceptor type impurity also varies significantly.

Structurally, the photoelectric converters of intrinsic based semiconductor materials with deep level multiply charge impurities are singletons photoresistant structures, or the so-called metal-semiconductor-metal structures with the formation of the structure of counter included Schottky diodes connected with the photoresistor. In the second case, the optical modulation of the Schottky barrier provokes a multiplying effect of the internal photocurrent (fig. 8). when doping an acceptor type impurity τ_n and τ_p vary by several decimal orders of magnitude. This leads to the fact that the when transferring to a different sub-band of power and spectral characteristics, high speed performance of photoelectric receiver with a deep multiply-charge acceptor type impurity also varies significantly.

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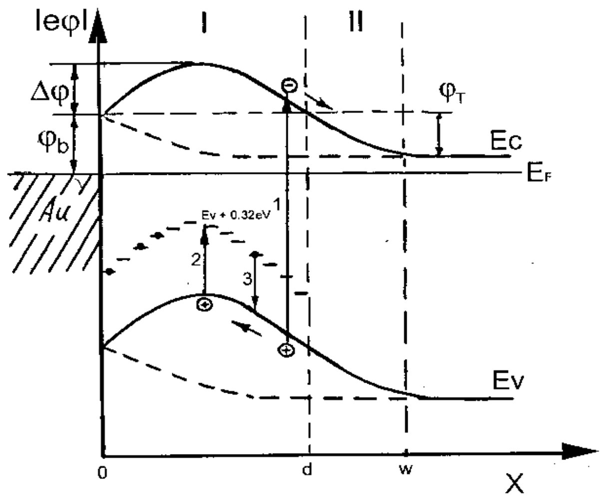

Fig. 8. The scheme of electronic transitions involving deep level impurity levels in SCR barrier structures: *1* reveals the effect of the influence of light from the excitation region of the intrinsic semiconductor; *2, 3* reveal thermal emission and recombination of holes; *d* reveals the region doped with deep level impurities; *W* is width of the SCR

Additionally, Fig.1 shows the presence of counter included barrier structures that can lead to the appearance of the spectral sensitivity characteristics (Fig.9) with the inversion of the sign photo-EMF in the region [11, 12].

Two-barrier semiconductor photoelectric receivers make it possible to produce a certain wavelength of the optical radiation only through a change in power supply of PEC [12]. Determining the wavelength of the optical signal does not depend on its power (Fig.9), the need for additional optical elements being eliminated.

Using the double-barrier photoelectric receivers in the optical channels provides a number of advantages. The possibility of transferring bipolar codes via the optical channel is realized when modulating optical radiation through only one level of power and the two lengths (more or less λ_0), which provides a self-locking feature and a narrow frequency of the signals being transmitted. Increase in noise immunity and the elimination of power losses in the optical communication channel when using double-barrier PEC is achieved due to the absence of additional optical elements for dividing the optical channel into two photoelectric receivers.

Moreover, the modulation of multi-value optical radiation wavelengths and power enables information signals space, noise and a spectral sensitivity branches of double-barrier photoelectric receivers being limited.

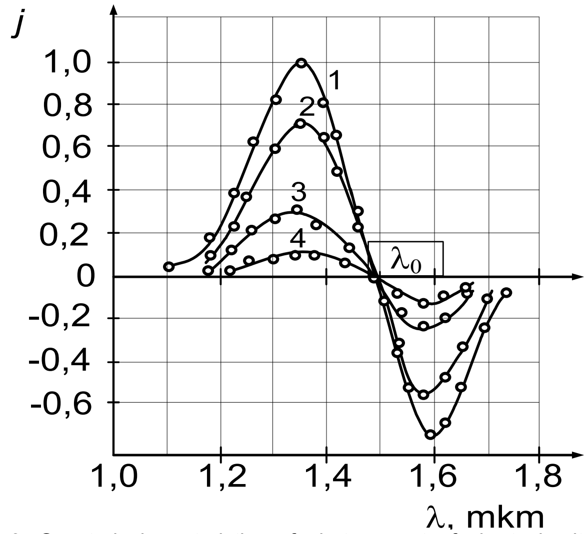

Fig.9. Spectral characteristics of photocurrent of short circuit of single-element two-barrier photoelectric converter (Ni-nGe(Cu)-Ni) at different densities of radiation power *1* – *J*=10 mcW/cm^2, *2* – *J*=5 mcW/cm^2, *3* – *J*=3 mcW/cm^2, *4* – *J*=1,5 mcW/cm^2

The application of two-barrier photoelectric receiver with the switch of output signal polarity with the λ_0 wavelength allows to transmit the level of reference signal at the λ_0 wavelength in the mode of optical signal power determination. Doing this allows to significantly increase the performance of the link in comparison with transmitting two levels of signal.

Thus, photoelectric converter with enhanced functionality and increased power range is a single-element device. In the multi-element devices special separation of the photo-receiving platforms causes time, phase, etc. distortions of the signal, increases devises dimensions, and creates extra interferences. The application in measuring tools and converters the multi-purpose compact single-element PECs, that are able to process input signal at many parameters , will allow to increase interference immunity, accuracy and validity of the information processed.

Resume

The use of photovoltaic cells to create semiconductors with deep multiply charge impurities provides a number of new quantitative and qualitative characteristics:

- to extend significantly (by several decimal orders) the dynamic range of the photoelectric receiver sensitivity with the impurities of the *p* and *n*-type;
- for PEC with acceptor impurities to implement spectral characteristics of sensitivity switched by external optical radiation or caused by the level change of signal excitation, the position change of the spectral characteristics maximum being up to 6.5 µm.

The developed model of recombination processes in semiconductors with multiply charge impurities designed for any number of charge states allows to predict and calculate the PEC basic parameters based on their own semiconductors with deep impurities.

The linear area boundaries of PEC with multiply charge impurities of the p-type can be controlled by varying the concentration of multiply charge impurities. For PEC with n-type impurities the boundary between the subbands of linear areas doesn't exist and the linearity change of the power characteristics does not exceed 1%.

The selection of a semiconductor material, of a deep impurity type and its concentration allows to create photoelectric receivers for a given range of optical power density, spectral range and functionality

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