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Photoelectric semiconductor converters with a large dynamic range

Abstract. *Semiconductors with deep multiply charged impurity are proposed as a basis for photodetectors with a large dynamic range of sensitivity. The model of recombination processes is used to develop photodetectors with extended dynamic range and functionality. It is shown that the use of such structures can significantly extend the dynamic range and sensitivity resulting in new functional properties of photodetectors with a simple structure.*

Streszczenie. *Do formowania przetworników fotoelektrycznych z rozszerzoną dynamiczną skalą czułości proponuje się wykorzystanie półprzewodników domieszkowanych głęboką wieloładunkową domieszką. Do opracowania przetworników fotoelektrycznych z rozszerzonymi funkcjonalnymi możliwościami i dynamiczną skalą wykorzystano model zjawisk rekombinacyjnych. Udowodniono, że wykorzystanie takich struktur pozwala istotnie poszerzyć dynamiczną skalę czułości oraz otrzymać nowe funkcjonalne właściwości przetworników fotoelektrycznych z prostą strukturą.* ***Półprzewodnikowe przetworniki fotoelektryczne z rozszerzoną dynamiczną skalą czułości*****).**

Keywords: photoelectric converter, dynamic range, intrinsic conductivity, multiply charged impurity, charge state.
Slowa kluczowe: przetwornik fotoelektryczny, diapazon dynamiczny, konduktywność samoistna, domieszka, stan ładunku.

doi:10.12915/pe.2014.05.16

Introduction

A number of applications where semiconductor photodetectors are used require an extended range of brightness conversion, for example, the high contrast imaging technique, weak navigational stars spectrophotometry, detection of weak optical radiation on a background of high brightness noise, etc. A high absolute contrast image is typical for scenes containing weakly illuminated objects and counter light [1]. Conventional photodetectors with limited dynamic range of sensitivity cannot provide a correct photosignal response when observing objects with large brightness or illumination contrasts. The problem of extending the dynamic range is especially actual for photodetectors operating in a charge storage mode, particularly for photodetecting CCD-sensors. Traditional solution of the this problem includes an expansion of the conversion range "from below" by increasing photodetector sensitivity. The main attention in this case is paid to noise reduction. The problem of extending the dynamic range towards higher illumination intensities – (expansion "from the top") is studied much less.

Illumination of photodetector at high intensity levels leads to the saturation of its sensitivity characteristic so adequate image of scene details cannot be obtained.

Experimental

Methods used to solve the problem of insufficient dynamic range of photodetector can be divided into three groups: a) hardware b) algorithmic (software), c) combined (hardware and algorithmic).

Methods from the first group require significant changes in the construction of photodetector [2], including the introduction of new materials and technologies, expensive cooling systems for CCD matrixes, powerful DSP processors and high rate ADC, that leads to essential expencies whereas the sensitivity range increases insignificantly. It is also possible to use composite photodetectors formed by two or more elements, each sensitive to its own density range of optical radiation intensity [3], that increase the complexity and geometrical area of the detector. Note also that the use of hardware methods of extending the dynamic range does not deteriorate the performance of the photodetector and, in some cases, leads to new functional properties.

The second group of methods implies the use of new data processing algorithms. For example, one method [4] implies obtaining the sequential series of images of the same object at different exposures throughout the entire range of brightness (exposure bracketing). After receiving a series of images for each pixel interpolated value of photosignal is calculated. Disadvantages of this algorithmic method are its limited applicability (only for static images), greater calculating time, higher costs of obtaining the interpolated image and the probability of artifacts.

The third group of methods includes BLC (Back Light Compensation) mode that is implemented in the form of switching operation thresholds of electronic shutter of the CCD matrix (or the objective aperture) and the AGC system so they become 10 - 20 % higher than normal [1]. As a result, the brightest objects (for example, a bright window) "cut in white" whereas mid-level objects (the face of a man standing in front of a window) are intensified becoming clearly visible [1]. Thus, BLC mode doesn't extends the dynamic range, but rather shifts it towards better observing of darker objects, due to the loss of bright objects. Mode modifications include an additional switch triggering automatic control circuits (video camera Watec, Sony, etc.). These modifications require increase of photodetector exposure time. Therefore "BLC" mode is useful in some cases of the video monitoring, but it cannot be used in an automatic mode, since the camera "does not know" if the operator is interested of the object in front of a brightly luminous surface or the most important is the surface image.

Results and discussion

Analysis of methods used to increase the dynamic range shows that hardware methods have advantages compared to software and combined methods because the use of hardware methods does not lead to deterioration of system performance and, in some cases, these methods can give new functional properties. In addition, an intrinsic semiconductors doped with deep multiply charged impurity are proposed to use as a basis for photodetecting device structures.

The choice of this basis is backed by the following considerations. Photoelectric converters are produced on a basis of the impurity conduction semiconductors (with a concentration of 10^{19} cm^{-3}) or intrinsic conductivity semiconductor. In the first case, a high sensitivity is reached, but at low power density the saturation of transfer characteristic is observed. In the second case, the saturation doesn't observed at high optical power densities, but the photodetector sensitivity is substantially lower [5, 6].

We propose to inject the certain multiply charged impurity in a predetermined concentration into the intrinsic semiconductor. Using the control mechanisms of the charge state of deep impurity centers [7] for the optical recharge of this impurity in a wide range of optical power densities provides the extension of energy characteristics linearity zone above the saturation threshold comparing to traditional intrinsic and extrinsic photodetectors. Thus the increased dynamic range of the energy characteristics of the photodetector is realized.

A proposed detector is performed in one volume of an intrinsic semiconductor doped with two or more deep multiply level impurities (fig. 1). For example, the energy diagram of an intrinsic germanium doped with gold forming the two deep levels impurity in multiple charge states is shown in fig. 2. Some impurities, such as Pt, generate three deep energy levels.

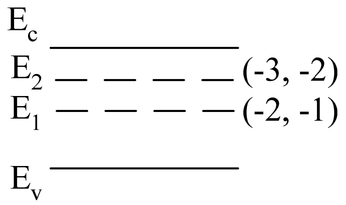

Fig.1. Energy diagram of the intrinsic semiconductor doped with deep impurity with several charge states (indicated in brackets)

Thus the photodetector structure is not complicated, the element size is not increased, and the characteristics of the device structure with deep multiply charged impurities are determined mainly by the nature of the recombination processes across impurity levels.

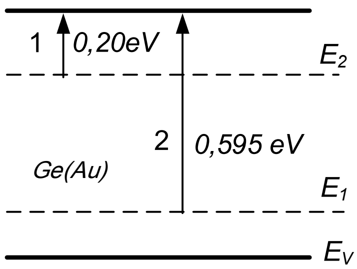

Fig.2. Energy diagram of Au-doped deep impurity Ge

Recombination processes modeling in photodetector structures with multiply charged impurities [8] showes that there are two linearity zones of energy characteristic. The specific form of characteristic depends on the type of impurity and concentration. Fig.3 shows the dependences of the concentration of copper ions in charge states (-3), (-2), (-1) (Fig.1) of optical radiation power density in n-Ge.

Automatic recharge of the charge states of deep multiply charged impurity with the increase of density optical power leads to the formation of two sub-bands of photodetector energy characteristics (fig.4). First sub-band corresponds to a linear recombination at low densities of optical power density below certain threshold value P_L while second sub-band of power characteristics linearity is observed at high optical power densities above P_H. For example, doped germanium photosensitivity for the semiconductor with three charge states (-1, -2, -3), is determined by the energy transitions at deep levels E_1 and E_2 (Fig.1). When the optical power is $P < P_L$ most impurity ions are in charge state (-3), whereas the concentration of the charge states (-2) and (-1) is significantly smaller and the energy transition 1 from level E_2 is realized (Fig.2). At the optical power $P > P_H$ most impurity ions are in multiply charged state (-1), the energy level E_1 is activated, and level E_2 don't operate. With sequential filling of multiply charged impurity levels during illumination under increasing power density the transfer characteristic based on the sum of levels E_1 and E_2 occupancy dependencies is realized.

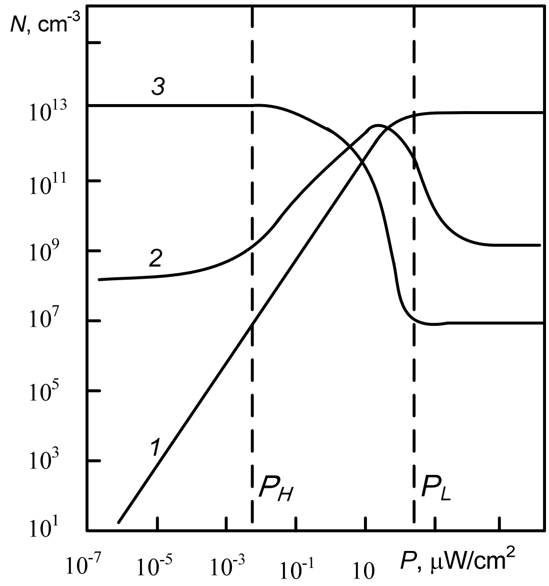

Fig.3. The dependences of the concentration of copper ions in the n-type germanium in the charge states (-3), (-2), (-1) (curve 3, 2, 1), respectively, on the optical radiation power density

The connection of level E_2 is characterized by transfer function (curve 2, Fig.4) with low sensitivity, but higher saturation threshold of the characteristic 1 in the high sensitivity sub-band. It should be noted that the transfer characteristic of type 1 is realized in the single-charged impurity photodetector (Fig.4).

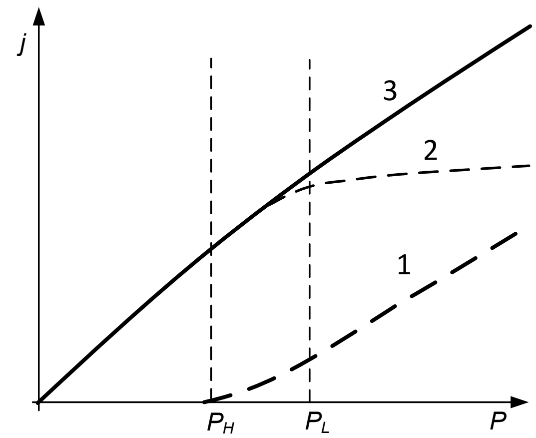

Fig.4. The transfer characteristic of the photodetector with three charge states of deep impurities

Thus, when the optical power is changed the change of concentration of the impurity charge states with different ionization energies and automatic switching between levels of the optical power as they are filled, respectively is happened. The result is an extension of the dynamic range of the photodetector sensitivity (curve 3, Fig.4). Note that within subbands $P > P_H$ and $P < P_L$ the energy characteristic of the photodetector is linear (Fig.5), and within the sub-band $P_L < P < P_H$ the shape of the energy characteristics may differs from linear. The boundaries of the sensitivity subbands can be controlled by varying the concentration of the multiply charged impurity and its type (Fig.6).

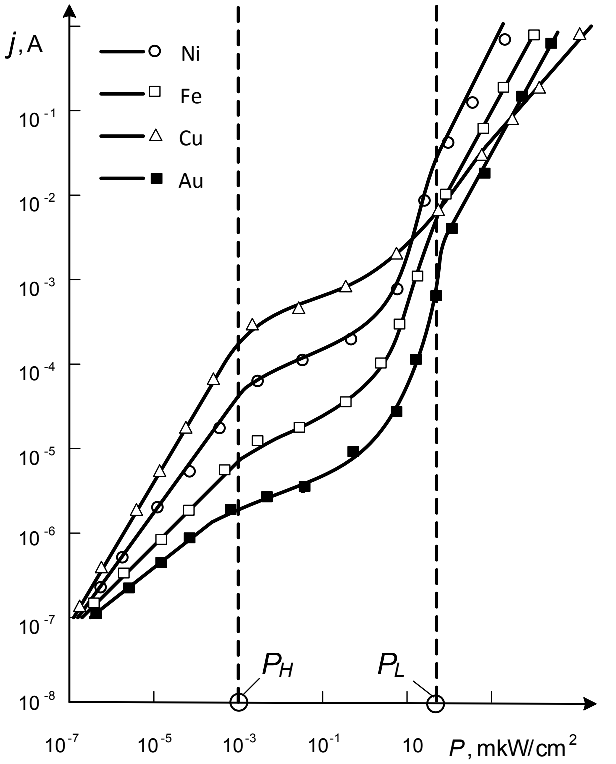

Fig.5. The experimental energy characteristics of the photodetector based on germanium doped with Ni, Fe, Cu, Au (λ = 1,7 μm)

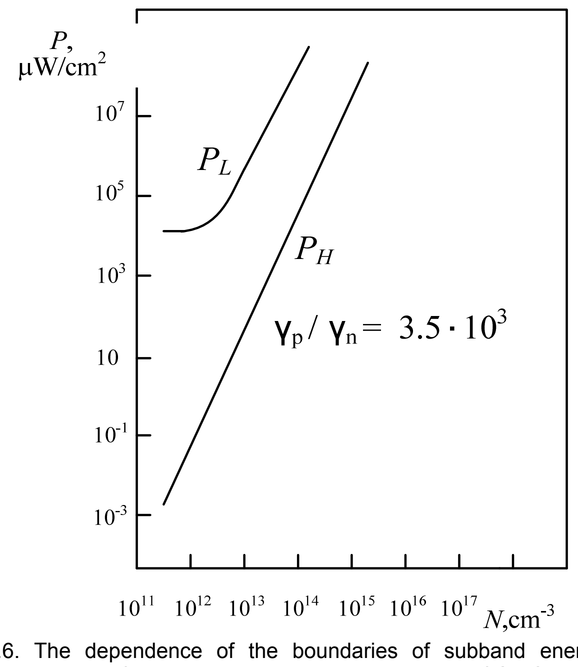

Fig.6. The dependence of the boundaries of subband energy characteristics of the acceptor impurity concentration of Ge(Cu)

Change in the type of multiply charged impurities leads to corresponding shifts of levels E_1, E_2 positions that in turn lead to shifts of the linear subbands boundaries and the detector spectral sensitivity. Thus, by varying the type and concentration of impurities it is possible to create not only photoelectric semiconductor converter (PSC) working in a predetermined density range of optical power [8], but also the optically controlled photodetectors [9].

For example, the additional illumination at a wavelength λ_0 can be used in a controlled photodetector to change the occupancy of deep impurity levels at the various charge states (fig.7). Depending on the power density of the signal at a wavelength λ_0 the various charge states of multiply charged impurities and, accordingly, the spectral characteristics with maxima at a wavelength of λ_1 or λ_2 are realized due to the peculiarities of impurity levels recharge depending on the intensity level of the controlled additional illumination. Therefore the impurity concentration at different charge states with different levels of ionization energy can be controlled by varying the radiation intensity from the intrinsic absorption zone (Fig.1, Fig.2). When the intensity of control radiation λ_0 is $P < P_H$ the level E_2 operates and the photodetector is sensitive to radiation with wavelength λ_1. When the intensity of control radiation λ_0 is $P > P_L$ the level E_2 operates and the photodetector is sensitive to radiation with wavelength λ_2.

Thus, the spectral sensitivity of the same photosensitive area of photodetector can be activated either in spectral region λ_1 or – λ_2 by variation of the additional controlled illumination intensity from the intrinsic absorption region (Fig.7). The dynamic range of photodetector sensitivity is significantly expanded when the intensity of control radiation is $P > P_B$ (Fig.4, 5) [10].

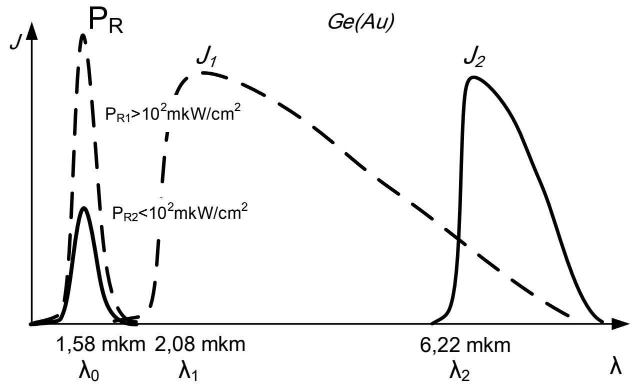

Fig.7. The switching of spectral characteristics of the deep multiply charged impurity photodetector by additional illumination at a wavelength λ_0

To realize the operational control of the spectral characteristics shape using conventional photodetectors it would be needed to use several photodetectors in one device. Each of them would be contained an optical filter element configured into various areas of the spectrum a beam splitting means, and combining electrical signals circuit.

Advantages of the proposed photodetector are the ability to control the spectral characteristics shape, realization of photodetector in the single volume of semiconductor material, expanding of the spectral and dynamic range, the exception of optical filter elements for the formation of the required form of the spectral characteristics using some photodetectors. For example, using the structure of Ge(Cu) allows the switching of the shape of spectral characteristic determined by the inclusion of the charge states at the energy levels Ev + 0,32 eV and Ec - 0.26 eV (wavelengths at the spectral characteristics of the shape fig.7 λ_1=2,9 μm and λ_2=4,77 μm). The structures with different semiconductors and multiply charged impurity can also be used.

Summary

Using semiconductors with deep multiply charged impurity creating PSC can significantly (by several decimal orders) extend the dynamic range of the photodetector sensitivity while retaining the fast response ability.

The developed model of recombination processes in the multiply impurities semiconductors may be used as a basis for the development of PSCs with enhanced dynamic range and functionality.

With appropriate selection of a semiconductor material, a type of deep impurity and its concentration it's possible to develop photodetectors for a given range of optical power density, spectral range and functionality.

REFERENCES

[1] Gvozdek M., Handbook of techniques for video surveillance. Planning, design and installation, *Technosphere*, (2010) (in Russian)

[2] Karimov A.V., Edgorova D.M., Giyasova F.A., Asimov T.M., Buzrukov U.M., Yakubov A.A., Features of photovoltaic characteristics of photovoltaic and electric structures, *Functional micro-and nanoelectronics*, (2007), n.4, 23-28 (in Russian)

[3] Revolutionary sensor blazes the way to a new era of high image quality – "Super CCD EXR" – www.fujifilm.com/photokina2008/pdf/release/super_ccd_exr_e.pdf.

[4] Kolobrodov V.G., Pivtorak D.O., Podolyan O.P, The method for producing a digital image with a large dynamic range, Patent of the Russian Federation 2470366, MPK G06T 5/50 (in Russian)

[5] Filachev A.N. Taubkin I.I., Trishenkov M.A., The state-of-the-art and the main directions of development of solid-state photonics, Fizmatkniga, Moscow, (2010) (in Russian)

[6] Filachev A.N., Taubkin I.I., Trishenkov M.A., Solid Photoelectronics, Fizmatkniga, Moscow, (2011) (in Russian)

[7] Gusev O.K., Vorobey R.I., Zharin A.L., Svistun A.I., Tyavlovsky A.K., Tyavlovsky K.L., The methodology and measuring parameters of objects with uncertain conditions, Minsk: Belarusian National Technical University (2010) (in Russian)

[8] Gusev O.K., Svistun A.I., Shadurskaya L.I., Yarjembitskaya N.V., Design and control of metrological characteristics of photovoltaic converters based on multiply charged impurities semiconductors. *Sensors and systems*, (2011), n.1, 22-24 (in Russian)

[9] Gusev O.K., Vorobey R.I., Svistun A.I., Tyavlovsky A.K., Tyavlovsky K.L. Shadurskaya L.I., Yarjembitskaya N.V., Controlled additional illumination photodetector, Patent of the Republic of Belarus 15840 MPK H 01L 31/16

[10] Gusev O.K., Svistun A.I., Shadurskaya L.I., Yarjembitskaya N.V., The identification algorithm of metrological characteristics of wide-range photovoltaic semiconductor converters with multiply impurities, *Devices and methods of measurements*, (2011), n.2 (3), 99-104

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