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Photoresponse in Ge/Si nanostructures with quantum dots

A.S. Nikolenko[1], **S.V. Kondratenko**[2], **O.V. Vakulenko**[3]
Taras Shevchenko Kyiv National University, Physics Department,
6, prospect Academician Glushkov, 03022 Kyiv, Ukraine
[1] *E-mail: Nikolenko_mail@ukr.net*
[2] *E-mail: kondr@univ.kiev.ua*
[3] *E-mail: vakul@univ.kiev.ua*

Abstract. Photovoltaic properties of Si samples with Ge quantum dots were studied. Photosensitivity spectra and current-voltage characteristics at 90 and 290 K were investigated. Negative photoconductivity of samples was revealed in the spectral range of 0.6 to 1.1 eV. Irregular temperature dependence of photo-emf in the temperature interval from 100 to 250 K was measured and analyzed.

Keywords: quantum dots, negative photoconductivity, photovoltaic properties.

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1. Introduction

Intensive theoretical and experimental investigations of self-assembled quantum dots (QD) were performed in recent years. It was found that a growth of a thin layer of one semiconductor in a matrix of another one with sufficient difference in lattice parameters results in formation of nanodimensional islands (Stranski-Krastanow growth mode) [1-4]. Properties of Si structures with Ge quantum dots were investigated by the methods of atomic force microscopy (AFM) [5, 6], photoluminescence [7, 8], Raman scattering [9, 10] and photoelectric spectroscopy [11-13] and became unique for creation of in principle new optoelectronic devices based on the quantum effects.

An atomic-similar spectrum of charge carriers in QDs lets to modify fundamentally characteristics of photosensitive structures with QDs in the case when a distance between levels considerably exceeds *kT*. For example, created were infrared photodetectors that are sensitive in the range of 3 to 5 μm and 8 to 12 μm due to intraband transitions [14, 15].

The problem of increasing the quantum efficiency and of widening the spectral sensitivity range up to far-infrared region for photodetectors based on silicon structures with germanium QDs needs more detail investigations of features of non-equilibrium processes. It is especially important to determine an influence of the energy structure of Si/Ge compositions with QDs of the second type on these processes. Measurements of spectral and temperature dependences of photoconductivity and photo-emf are very informative methods to solve this problem.

2. Experimental technique

The samples under this study were grown using molecular-beam epitaxy. On the (100) oriented 7.5 Ohm·cm *n*-Si substrate, grown was a thin Ge layer that was covered with the surface Si layer of the thickness 20 to 40 nm. This procedure was recycled 5 times [16]. To have an opportunity to control the size and the surface density of QDs by the AFM method, the Ge layer was grown in the end of these procedures. From the analysis of the AFM image, the surface density was estimated to be $2\cdot10^9$ cm^{-2}. The average size of the dot base length was found to be about 100 nm, the average height was about 15 nm.

The ohmic Al contact was formed on the back side of the Si substrate. Formation of the second contact was realized by evaporation of the rectangular Al frame of 5×8 mm on the Ge surface.

Measurements of the spectral dependences of the photoconductivity and the photo-emf were performed using the standard infrared spectrometer in the spectral range of 0.6 to 1.2 eV (~ 2 – 1 μm). Unmodulated light from the globar source after passing through the monochromator was focused on the Ge surface of the sample in the middle of the rectangular Al contact.

The signal of the photoconductivity was measured by the circuit with compensation of the dark current. To measure the direct current, a highly sensitive amperemeter was connected up to the diagonal of the bridge circuit. Values of the resistors in the circuit were chosen in such a manner to make equal to zero the value of current through the amperemeter in the absence of illumination. Photo-emf was measured under no-load conditions. Spectral dependences of the photoconductivity and the photo-emf were corrected to constant number of quanta of the excited illumination using the pyroelectric optical detector.

3. Results and discussion

The measurements of the current-voltage characteristics were carried out for the investigated structures. The form of the current-voltage curves was found to be essentially nonlinear both at T = 290 K and 90 K. As was expected, the significant change of the current value under illumination took place only at the reverse bias. Such fact indicates existence of potential barriers in the sample [17, 18]. Therefore, there are initial conditions for spatial separation of non-equilibrium charge carriers and appearance of the photo-emf.

Investigated structures were found to be photosensitive. The generation of the lateral photo-emf was observed under illumination in the Si fundamental absorption region ($h\nu > 1.1$ eV at $T = 290$ K). In the infrared region, where Si is transparent, generation of the photo-emf was not observed. Fig. 1 shows the spectral dependences of the photo-emf at $T = 90$ K and 290 K. It was found that, at $T = 90$ K, the photo-emf signal value was approximately 50 times less than at $T = 290$ K. At lower temperatures, the longwave spectrum edge shifts to the shortwave region. This fact can be explained by the Si bandgap increase with the decrease of the temperature. The considerably less value of the photo-emf at $T = 90$ K can be explained by the trapping of non-equilibrium carriers of one type in the region near Ge/Si interface.

The same situation takes place in the heterostructures with the QDs of the second type, the Ge/Si heterostructure belongs to these systems. Thus, in the heterostructure, relative positions of the energy bands are determined by the structure and the composition of the semiconductor materials that form the heterostructure. If the band diagram provides the minimum energy value for the electrons as well as for the holes in one of the semiconductors, then heterostructure belongs to the first type. If the least energy state for the electrons is situated in one of the semiconductor materials and for the holes in another one, then heterostructure belongs to the second type of heterostructures. It follows that, in the heterostructure of II type with two heterojunctions, formation of the potential well is possible only for the charge carriers of the one type. Potential barrier exists for another type of the charge carriers [19]. Fig. 2 shows the energy scheme of the Ge/Si heterostructure.

In this system, indirect electron transitions from the valence band of QDs to Si conductivity band are possible. The absorption maximum caused by such transitions was observed in the range of 760 – 770 meV [20]. In our case, the photoexcited charge carriers formed as a result of the indirect transitions, don't give a contribution to the photo-emf signal in the infrared region ($h\nu < E_g^{\mathrm{Si}}$).

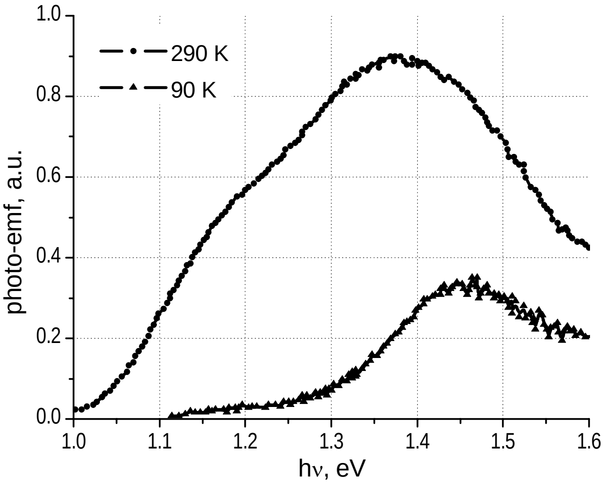

Fig. 1. Photo-emf spectral dependence at the temperatures 290 and 90 K.

Existence of the potential well results in localization of the photoexcited holes in the QDs, which lead to change the potential in ambient medium. In Fig. 2, the solid line shows a result of bending the bands in the Ge/Si heterostructure due to localization of the holes in the QDs. As a result of such change of the potential is possibility for creation of the quantum well for the electrons around the QDs and formation of the bound states in this system. In the heterostructures of the second type, localized states for the electrons and for the holes are formed in the opposite sides of the heterostructure. The holes and electrons in such states are spatially separated and transition between them is indirect in space [20]. It should be noted that, though the photoexcited carriers are spatially separated, they cannot give the contribution to the signal of the stationary photo-emf, as the localization of the carriers of one type makes it impossible to observe the photo-emf of such type.

Also investigations of the spectral dependences of the stationary photoconductivity were carried out for the investigated structures. The stationary photoconductivity was measured by means of the compensation method that was realized using the bridge circuit.

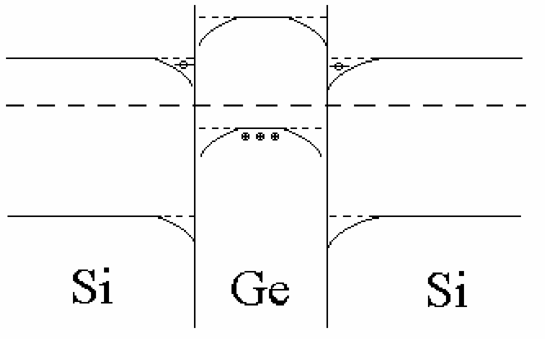

Fig. 2. Energy scheme of the Ge/Si sample with QDs.

It was found that the structures were photosensitive in the range of $h\nu > 0.6$ eV (Fig. 3). The signal in the region of $h\nu > 1.15$ eV (Si bandgap at $T = 90$ K [21]) was caused by the interband transitions in silicon. But at $T = 90$ K, the change of the current value was observed when the structure were illuminated by light in the range from 0.6 to 1.15 eV, where Si is transparent. Furthermore, in this range the decrease of the current value was observed as compared with the value in absence of illumination, in other words, the negative photoconductivity was observed. In the most known cases of photoconductivity observation in semiconductors, the material conductivity increases under the illumination due to interband transitions. In the shortwave region ($h\nu > 1.15$ eV), the interband transitions in silicon occurred, and the current value increased under illumination.

The negative photoconductivity in investigated samples in the region of $h\nu < 1.15$ eV can be explained by realization of abovementioned indirect in space transitions in the Ge/Si structure with QDs. Due to such transitions, photoexcited holes are accumulated in Ge QDs, and conduction electrons are accumulated in the region around the QDs in the silicon layer. As a result, the formation of the quantum wells for the electrons in the Ge/Si interface in the silicon layer where accumulation (capture) of the photoelectrons is possible. Such situation in our case results in the decrease of the conduction electrons number and the current value through the sample, which was observed under the illumination in the region of $h\nu < 1.15$ eV. Obviously, increase of the current value under the illumination in Si fundamental absorption region caused by the domination of the photoeffect in the *n*-Si substrate.

We supposed the capture of the charge carriers of one type to explain the essentially smaller value of the photo-emf at $T = 90$ K as compared with corresponding value at room temperature. As well known, for appearance of stationary photo-emf, spatial separation of mobile charge carriers of both types must occur. The capture of the photoexcited carriers at least of one type must decrease a value of the photo-emf. For more detail study of this problem, the investigations of the photo-emf temperature dependence were carried out. The temperature dependence of the photo-emf was measured in the temperature range from 100 to 350 K. The signal of the photo-emf was measured under the no-load conditions at the peak of spectral sensitivity. Fig. 4 shows the shape of the obtained temperature dependence.

As follows from Fig. 4, the temperature dependence of photo-emf has two specific intervals. The first interval of the temperature dependence is characterized by increase of the photo-emf signal in the temperature range from 100 to 250 K, the second interval is characterized by decrease of the signal in the temperature range 250…350 K. Also it should be mentioned that these intervals differ in signal increase character that indicates existence of two different physical processes which influence on the form of the temperature dependence of photo-emf in different temperature intervals. To find the activation energies of these processes, the temperature dependence was represented in the form of the photo-emf logarithmic dependence on $1/kT$. The activation energies of the processes were found as the tilt of the approximation line in the linear ranges of the temperature dependence (see Fig. 4). Thus, it was found that in the temperature range from 100 to 250 K the activation energy is 0.1 eV and in the temperature range from 250 to 350 K – 0.35 eV.

The increase of the photo-emf signal under heating in the range of 100…250 K can be explained in the following way. Besides the capture of the photoexcited electrons in the energy level near the Ge/Si interface (see Fig. 2), there is thermal ejection of the captured carriers from this level to the Si conductivity band. It is reasonable that with temperature increase the probability of the latter process increases and the capture probability decreases. This fact agrees with the existence of negative photoconductivity, which was observed only at low

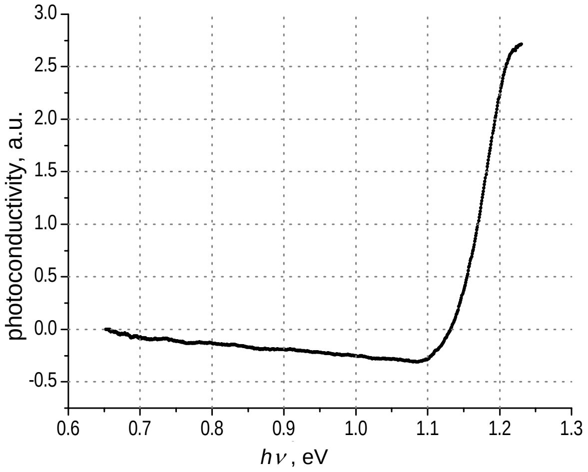

Fig. 3. Photoconductivity spectral dependence at $T = 90$ K.

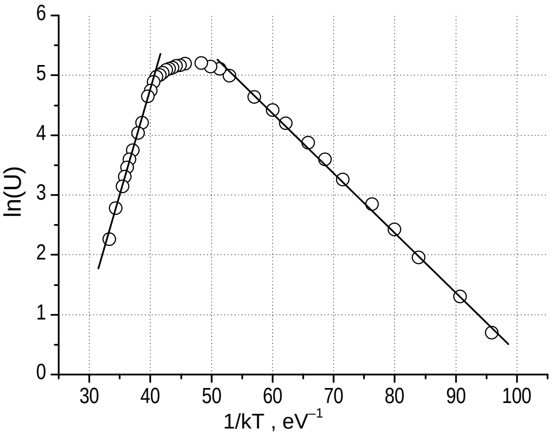

Fig. 4. Photo-emf temperature dependence.

temperatures (T = 90…200 K) and was explained by the capture of the photoexcited carriers.

At higher temperatures, in the range T = = 250…350 K, the influence of another process becomes more noticeable. A decrease of the photosensitivity under heating in this range caused by a charge carrier lifetime decrease, which takes place in the most of semiconductor photodetectors [9]. But this assumption requires more detail investigations.

4. Conclusions

Negative photoconductivity of the samples in the spectral range from 0.6 up to 1.15 eV is a result of the indirect in space optical transitions in the Ge/Si structure. Due to these transitions accumulation of the photoexcited holes occurs in QDs and, as a result, the localization of the conduction electrons in the regions near the QDs.

The form of the obtained temperature dependence indicates existence of two different processes, influence of which on the form of the photo-emf temperature dependence in different temperature intervals. The increase of the photo-emf signal in the temperature range from 100 up to 250 K was explained by availability of traps for charge carriers and by their thermal ejection from the traps under heating.

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