ИЗВЕСТИЯ ВЫСШИХ УЧЕБНЫХ ЗАВЕДЕНИЙ
Т. 55, № 8/3 ФИЗИКА 2012

УДК 621.31:535.215

K.A. LOZOVOY, A.V. VOYTSEKHOVSKIY, A.P. KOKHANENKO, A.M. TURAPIN, V.G. SATDAROV, E.A. KALIN

Si/Ge-BASED PHOTOSENSITIVE NANOHETEROSTRUCTURES FOR OPTICAL COMMUNICATION SYSTEMS

This scientific work is devoted to investigation of possibility of creation of photosensitive structures based on Si/Ge nanoheterostructures for optical communication systems. Analysis of methods of obtaining such structures is conducted. Results of modeling of dependence of parameters of self-organized quantum dots arrays of Ge on crystal surface Si(001) on growth condition are represented. Also some experimentally received samples are shown.

Keywords: *QD, MBE, optical communication systems, photodetectors, photosensitivity.*

In recent years, perspectives of Ge-in-Si-based semiconductor materials employment in optoelectronics have appeared. Such materials contain nanodimensional clusters of Ge (quantum dots) “embedded” in Si matrix. Si/Ge light-emitting devices and photodetectors allow silicon technology to successfully compete with traditional optoelectronic materials, such as $A^{III}–B^{V}$ compounds. Enhancement of efficiency of Si with Ge quantum dots (QD) nanoheterostructures-based devices is possible due to low-dimensional quantization effects. These effects are revealed when geometrical sizes of nanostructures are about 10 nm and less. Besides that high enough surface density of these structures arrays is necessary [1].

One of the most important directions of development of integrated communication system (information processing and transmission) is designing of fiber-optic transmission lines and photonic devices operating in quartz spectral window near wavelengths of 1.3 and 1.55 μm. Creating of the hole set of components of fiber-optic communication line (FOCL), including light-emitting devices and photodetectors, on one chip is seems to be relevant. For such systems cost reduction more components must be done with using of traditional methods of silicon technology.

In this work analysis of possibility of creation of IR region photodetectors based on nanoheterostructures with QD of Ge in Si was conducted. In papers [2–5] photodetectors (PD) for FOCL applications were obtained and investigated. At wavelength λ = 1.3 μm quantum efficiency of about 1– 4.2 % is reached. Dark current densities at 1 V bias voltage and room temperature are 10^{-4}–10^{-3} A/cm^2 and considerably exceed those for Si and Ge diodes.

In the work [6] authors report about creation of Ge/Si PD, containing from 12 to 36 layers of QD as an active element and grown by the method of molecular beam epitaxy (MBE) on oxidized silicon surface at different temperatures. Increasing of quantum efficiency was reached due to realization of waveguide structure of PD with using of waveguide walls total internal light reflection. Photosensitive layers were formed on silicon-on-insulator substrates as lateral waveguides with width of 50 μm and length from 100 μm to 5 mm. It was found that maximum quantum efficiency occurs in structures with less than 3 mm length at reversed bias voltage more than 3 V and reaches 21 and 16 % for wavelengths of 1.3 and 1.55 μm respectively. Such high values of quantum efficiency were obtained due to high density of Ge QD in active layers and due to effect of repeated internal reflection. In the work [7] in similar structures sensitivity 1.2 A/W at 1.55 μm was reached.

After making the review it is possible to conclude, for realization of advantages of PD with QD it is essential to decrease QD sizes and increase density of QD in order to achieve minimum dark current without losing high quantum efficiency of conversion. Between different types of PD (photodiodes, phototransistors, waveguide photodiodes) maximum quantum efficiency have waveguide photodiodes because of more complete absorption of radiation.

In this work results of modeling of dependence of parameters of self-organized QD arrays of Ge on crystal surface Si(001) on growth condition are represented. All estimations are based on kinetical model. Since in the process of growth Ge islands form spontaneously, its morphology can be governed by changing growth conditions. These conditions are temperature of substrate, growth rate, nominal thickness of Ge. In addition, arrays of Ge islands grown on different oriented or previously oxidized Si surfaces have different properties. Alternative methods of defining of properties of such systems are using of surfactants and lithography or radiation treatment.

After the analysis of literature data on the problem of growth of QD Ge on Si by MBE conclusion was made that the most suitable model for different stages of growth describing is kinetical model from the work [8]. With knowing of parameters of heteroepitaxial system, that can be partially defined from experimental data, this model allows to calculate lateral size distribution function of QD and their surface density. This model also explains experimental dependences of average lateral size and QD density on growth temperature, growth rate and effective thickness of Ge.

In process of work dynamics of processes at beginning stages of QD growth were studied, program for calculating of characteristics of QD arrays was written, computer modeling and numerical experiments on defining of heteroepitaxial system parameters dependence on growth conditions were conducted. Temperature dependence of Ge on Si surface diffusion coefficient was used.

After the preliminary estimates growth conditions for obtaining QD array with given parameters were chosen. Synthesis of structures was done on MBE installation "Katun-100". As a result of growth experiments was achieved surface density of Ge islands that exceeds value of 10^{11} cm^{-2}.

Surface investigation of received samples was done with the help of atomic-force microscope (AFM) NT-MDT SOLVER. AFM picture of sample grown at T = 350°C temperature and growth rate V = 0.45 ML/s (monolayers per second) was obtained (Fig. 1).

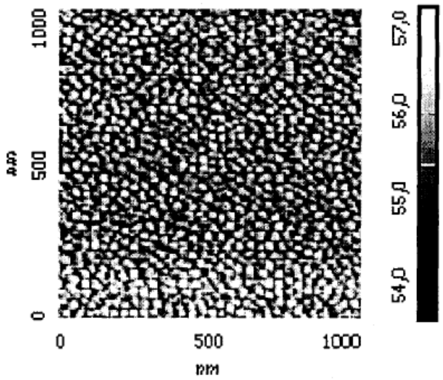

Fig. 1. AFM picture of Ge islands on Si(001) surface.

Effective thickness of Ge was 6 ML. Results of synthesis correlate well with the data from used method of calculation of parameters of self-organized arrays of Ge QD on Si substrate at different growth conditions.

With knowing of morphology of nanoclusters, that is lateral size distribution function and surface density of islands, it is possible to calculate energy spectrum of electron, wave functions of electron in QD, and then absorption coefficient and its spectrum. Otherwise, in order to create structures with absorption coefficient maximum at 1.3 and 1.55 μm it is possible to estimate suitable for it average lateral size of QD, and then pretend optimal for this MBE growth conditions.

Also using of multilayer Bragg reflectors, based on materials systems Si/Ge, for creating a resonator on wavelengths λ = 1.3 and 1.55 μm for absorbed optical power increasing is offered.

REFERENCES

1. Kang L.Wang, Dongho Cha, Jianlin Liu, et al. // Proc. IEEE. – 2007. – V. 95. – No. 9. – P. 1866-1882.
2. Elcurdi M., Boucaud P., and Sauvage S. // Appl. Phys. Lett. – 2002. – V. 80 – No. 3. – P. 509–511.
3. Tong S., Wan J.L., and Wang K. // Appl. Phys. Lett. – 2002. – V. 80. – No. 7. – P. 1189–1191.
4. Masini G., Colace L., and Assanto G. // Appl. Phys. Lett. – 2003. – V. 82. – No. 15. – P. 2524–2526.
5. Elving A., Hansson G.V., and Ni W.-X. // Physica E. – 2003. – V. 16. – P. 528–532.
6. Якимов А.И., Двуреченский А.В., Кириенко В.В. и др. // ФТТ. – 2005. – Т. 47. – № 1. – С. 37–40.
7. Morse M., Dosunmu O., Yin T., et al. // Proc. SPIE. – 2008. – V. 6996.
8. Дубровский В.Г. // ФТП. – 2006. – Т. 40. – № 10. – С. 1153–1160.

Tomsk State University, Tomsk, Russia
E-mail: lka@sibmail.com

Поступила в редакцию 15.06.12.

Lozovoy Kirill A., student;
Voytsekhovskiy Alexander V., professor;
Kokhanenko Andrey P., professor;
Turapin Alexey M.;
Satdarov Vadim G., student;
Kalin Eugeniy A., student.