Vol. **113** (2008) *ACTA PHYSICA POLONICA A* No. 3

Proceedings of the 13th International Symposium UFPS, Vilnius, Lithuania 2007

Laser Induced Self-Organization of Nanohills/Nanowires in SiO_2/Si Interface

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The aim of this work is to study optical properties of self-organized Si nanohills formed on the SiO_2/Si interface after pulsed Nd:YAG laser irradiation. Nanohills on Si surface give strong photoluminescence in the visible range of spectrum, with a long wing in red portion. This property is explained by charge carrier quantum confinement in nanohills/nanowires.

PACS numbers: 75.47.Gk, 75.47.Lx, 07.57.Kp

1. Introduction

Semiconductor nanostructures have attracted a considerable attention because they are building blocks for nanoscale electronics and photonics devices. At present they are under intense investigation in solid-state physics, especially quantum dots (QDs), quantum wires (QWs) and quantum wells [1, 2]. In the case of nanosized structures the energy bands are strongly influenced by volume of the structure, which leads to crucial change in the semiconductor properties: (1) the electroconductivity, due to the change of free charge carrier concentration and mobility; (2) the optical parameters, for example, the absorption coefficient, reflectivity, radiative recombination efficiency; (3) the mechanical and heating properties. The increase in the investigations devoted to homogeneous structures, such as well-defined one-dimensional and axial heterostructures, multiheterostructures and core-shell nanowire heterostructures generated a great interest in their potential applications.

Fabrication of nanostructures without lithographic process, using self-assembling processes is a promising technique for future nanoelectronics. In the latter case, the microscopic structures on the surface, or strain induced by lattice mismatch are brought into play. At present there exists a number of well elaborated methods for the formation of nanostructures, for example, molecular beam

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epitaxy [3], ion implantation [4], and laser ablation [5, 6]. The methods based on self-formation of nanosize silicon structures (nanowires, nanodots, nanorods, nanohills) are also very important for future Si-based nanoelectronics and opto-electronics, since Si is a basic material in the microelectronics. Photoluminescence (PL) from Si and Ge nanoparticles implanted into SiO_2 layer has been detected by several scientific groups in IR, red, and blue-violet regions of the spectra [7–9].

The nanohills are known to grow on the mechanical scratches after laser irradiation. Recently, we have shown the possibility for formation of nanohills on the free surface of Si single crystal after Nd:YAG laser irradiation [10]. A visible PL spectrum of the irradiated surface of Si sample was found to be wide, with the maximum of PL at 770 nm. This is a dramatic effect since the PL energy is much higher than the indirect band gap of Si. We connect this PL property with a quantum confinement effect on the top of nanohills. Since SiO_2 is a natural oxide it is very important to study the influence of SiO_2 layer in SiO_2/Si structure on the PL spectrum. The aim of this work is to investigate optical properties of Si nanostructures formed on the SiO_2/Si interface subjected to pulsed Nd:YAG laser radiation.

2. Experiment

n and p-type Si wafers with thickness of SiO_2 top layer 0.2 μm, which has been grown by thermal oxidation method, were used. The experiments were performed in the ambient atmosphere ($P = 1$ atm, $T = 20°$C, and 80% humidity). Second harmonic radiation from a pulsed Nd:YAG laser (pulse duration 10 ns; wavelength 532 nm; power 1 MW) was normally incident on the surface of SiO_2/Si structure. The spot of laser beam of 3 mm diameter was scanned over the sample surface in 1 μm or 2 μm steps.

In diagnostics the atomic force microscope (AFM), PL and micro-Raman backscattering setups were used. The PL spectra was excited by the 488 nm line of a He–Cd laser, while micro-Raman backscattering spectra were excited by Ar ion laser with $\lambda = 514.5$ nm. In Fig. 1a and b there are shown the AFM 3D image of Si surface of SiO_2/Si structure after irradiation by Nd:YAG laser with intensity $I = 2.0$ MW/cm^2 and the same 3D image of AFM of Si surface after subsequent chemical etching by HF. The PL spectra of the irradiated (curves 1 and 2) and non-irradiated (curve 3) surfaces of SiO_2/Si at the intensity of laser radiation up to 2.0 MW/cm^2 are shown in Fig. 2.

2. Discussion

Figures 1a and b show that the surface of SiO_2 layer is smooth, "stone-block" like. This is because SiO_2 layer is covered by very sharp Si nanohills, Fig. 1b, which appear on the SiO_2/Si interface after irradiation by laser. The SiO_2 layer was fully removed from SiO_2/Si structure by HF acid. The PL in a visible range of spectrum with maximum at 2.05 eV was found in SiO_2/Si structure after irradiation by

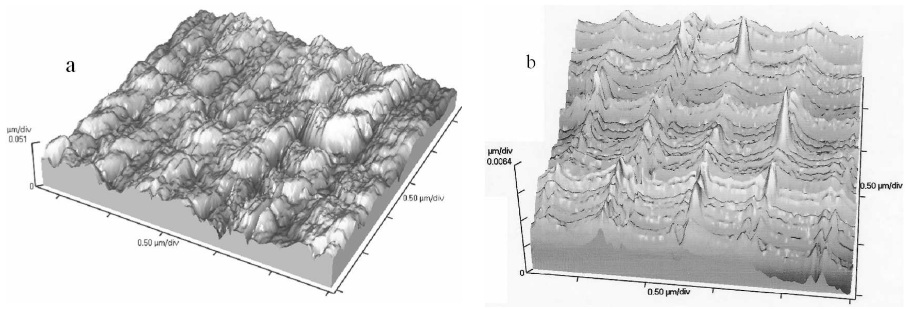

Fig. 1. AFM 3D images of (a) SiO_2 surface after irradiation of SiO_2/Si structure by Nd:YAG laser at $I = 2.0$ MW/cm^2 and (b) Si surface after subsequent removing of SiO_2 by HF acid.

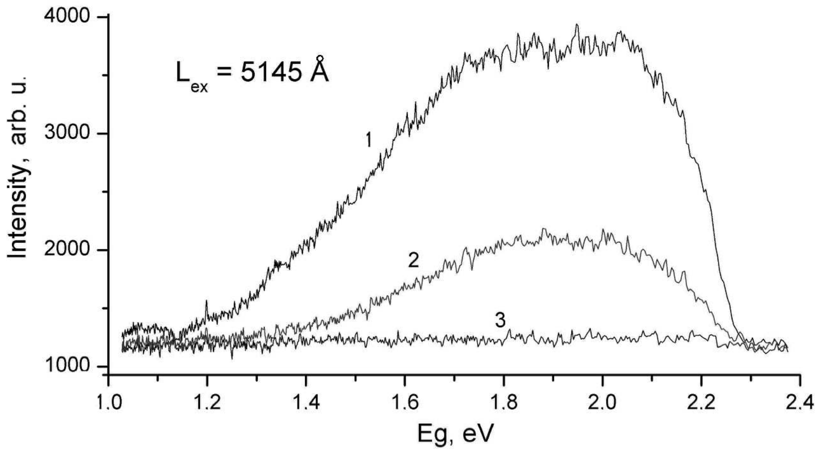

Fig. 2. PL spectra of the irradiated SiO_2/Si structure at the intensity of the laser radiation up to 2.0 MW/cm^2 (1 and 2), and after removing of SiO_2 layer by chemical etching in HF acid (2), and the PL of the unirradiated surface (3).

laser with $I = 2.0$ MW/cm^2, as shown in Fig. 2. The PL of this structure after chemically etching away of SiO_2 layer by HF acid is similar. It appears in the same range of the spectrum, with the position of maxima unchanged. It means that the PL is not connected with local Si–O vibrations at Si–SiO_2 interface [8]. Therefore, we explain our results by quantum confinement effect in nanohills. Decrease in the PL intensity can be explained by increase in the reflection index of the structure after removing of SiO_2 layer. We can see that the visible PL spectrum of SiO_2/Si structure is wide and non-symmetric, with gradual decrease in the intensity in IR range of the spectra. These processes give a dramatic effect on PL, with the emitted photon energy being much higher than the indirect band gap of Si.

In conclusion, we have found a new method for formation of a wide photoluminescence spectrum by indirect gap elementary semiconductors. We think that the shape of the spectra is due to the quantum confinement effect and nonuniformity of nanohills/nanowires after pulsed Nd:YAG laser irradiation. Usually this PL property is obtained by a conventional method, the molecular beam epitaxy, where molecular component concentration is changed layer by layer. The present method allows to obtain wide PL spectrum in elementary as well as ternary compound semiconductors, for example CdZnTe, or binary compound solid solution, for example SiGe structure.

Acknowledgments

This work was supported by the Latvian Council of Science under the project No. 05.0026.10.

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