Correlations between the surface morphology and electronic properties of porous multilayer structures with quantum InGaAs layers

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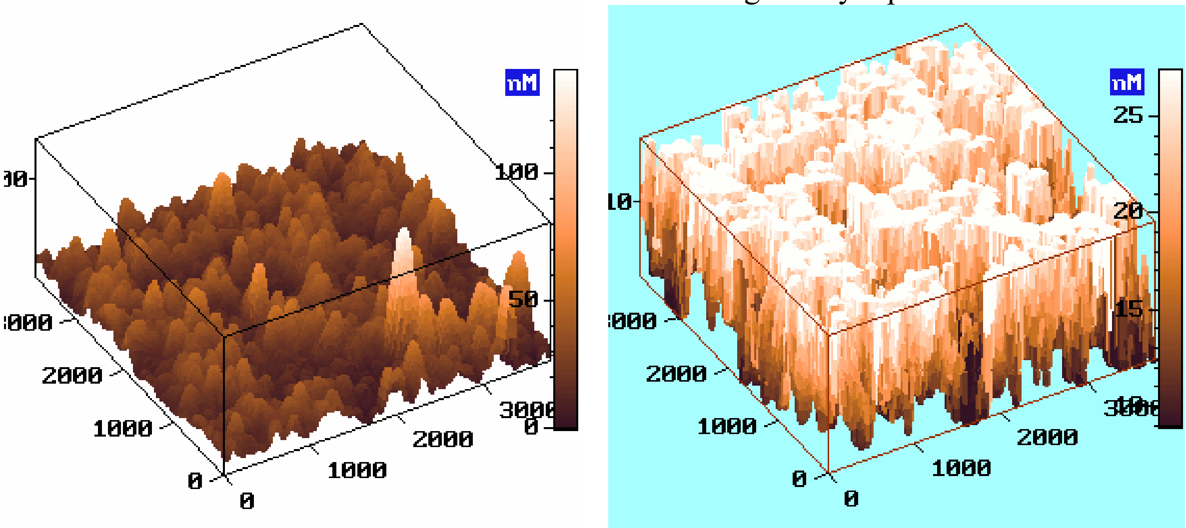
Recently, porous materials on the base of semiconductor crystals arouse greater interest as photon crystals in terms of opto-electronic applications and formation of arrays of nano-elements with one- and zero-dimensionality. The crystals of porous silicon have been developed best to date. The obvious trends in this field now are towards using other materials for electrolytic etching, decreasing the diffraction lattice period to have photon crystals operate at smaller wavelengths, and study of porous compositions with microporosity. Besides, porous structures attract close attention as subjects for study of low-dimensional fundamental physical properties.

In this work the properties of porous conducting two-dimensional InGaAs layers embedded in GaAs or InAlAs porous dielectric matrix are discussed. The influence of the electrochemical etching time of samples, their porosity and surface morphology on the optical and electrophysical characteristics of the structures with a low-dimensional electron gas has been investigated. Epitaxial multilayer GaAs/InGaAs structures of the first type have been grown on isolated GaAs substrates by the MOCVD method. These compositions contained from 1 to 11 InGaAs single quantum wells embedded into the GaAs matrix with the GaAs barrier layer thickness about 160 nm (№ 30-54). The second type of the test structures is represented by the InAlAs/InGaAs/InAlAs composition with one InGaAs quantum well (№ 401), grown by GSMBE. The top InAlAs layer covering a 40 nm thick InGaAs electron transport channel had the thickness of about 100 nm. The porous samples have been produced by the electrochemical etching of the structures [1] in alcohol solution of FH acid at a current density of about 0.05 A/cm^2.

A change in the surface morphology due to the formation of a porous surface structure in the process of etching has been studied by the scanning probe microscopy (SPM). Modification of the surface structure, the change of porosity of the samples, the size of pores and nano-islands formed on the surface, the porous layer thickness can be traced with this method depending on the etching time of the samples. Initially the heteroepitaxial structures had a rough surface with the depth of surface imperfections reaching 4 nm [2,3]. Varied-depth sections of the porous layer show that the porous two-dimensional (2D) InGaAs layer in the structure with one quantum well nearest to the surface is formed in our case at the initial stage of the etching process. The change in the surface morphology of the multilayer structure during the etching process induces an inhomogeneous potential in the plane for the depth layers, that modulates the energy band edges in the quantum wells of the structure. Further etching of the sample leads to an increase in the material porosity and to formation of arrays of islands on the surface of structure (Fig.1a). Narrowing of the InGaAs layer area with an increase in the etching time leads to formation of a complex two-dimensional network of conducting quantum threading. We can see this in Fig.1 where the SPM image of the surface of sample № 401 after 10 minutes of etching is shown. We see here that the visual depth of the top layer etching up to the undoped InAlAs buffer layer is about 140 nm (Fig.1a). The thickness of the real porous layer is about 50 nm, which corresponds to the thickness of the InGaAs electron transport layer in the sample. The tomography of the SPM image at an 18 nm height from the low boundary of the InGaAs layer (it is approximately the middle of the InGaAs transport channel in the structure) is shown in Fig.1b. The geometry of the sample suggests that the electron current is directed along the InGaAs layer plane, that is why, in addition to the vertical pores, we see wide etching areas which form an irregular two-dimensional net in the layer. The micro-island chains in the porous InGaAs layer with 2D electron gas make quantum threading, and this system can be represented as a 2D network composed of 2D or 1D quantum wires. The size of wires in our case is 40 nm in the vertical direction and about 100 nm in the horizontal direction along the layer plane.



a b

Fig.1. SPM images of a porous structure № 401 after 10 min etching time (a - 3D image of the surface of porous layer, b – the tomography of the SPM image at a 18 nm height from the transport InGaAs layer bottom).

Formation of a porous structure of a quantum InGaAs layer during a longer etching time may result in additional real spatial confinement in the layer plane and formation of two-dimensional (2D) nets of quantum 1D wires. The effect of transformation of 2D electron energy spectra into one-dimensional spectra in a porous multiplayer structure has been demonstrated by analysis of the photoluminescence (PL) line position and width versus etching time of the samples (see [1-3]). It is obvious (Fig.2), that the increase of a sample etching time will result in an increase of the layer porosity. At longer etching there are separate InGaAs islands not connected with each other on the buffer layer surface.

The use of multilayer structures in our experiments permitted us to etch a sample up to two hours, the structures still conducting electric current. The visible depth of pores for InGaAs/GaAs multilayer structures did not exceed 200 nm [2,3] according to the SPM data.

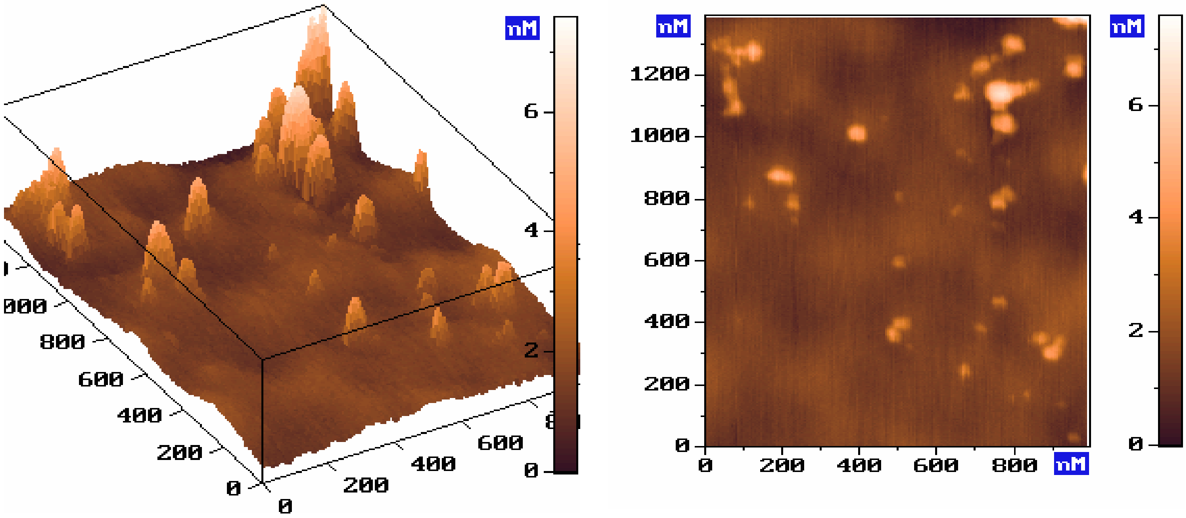


Fig.2. SPM images of porous structure № 401 after 30 min etching time (a - 3D image, b - 2D image) - InGaAs quantum dots on the surface of InAlAs buffer layer.

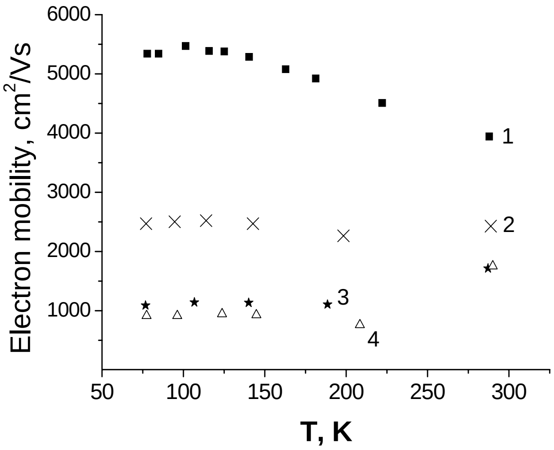


Fig.3. Electron mobility versus measurement temperature for sample № 54 after the etching time: 0 min (symbol 1), 10 min (2), 20 min (3), 30 min (4).

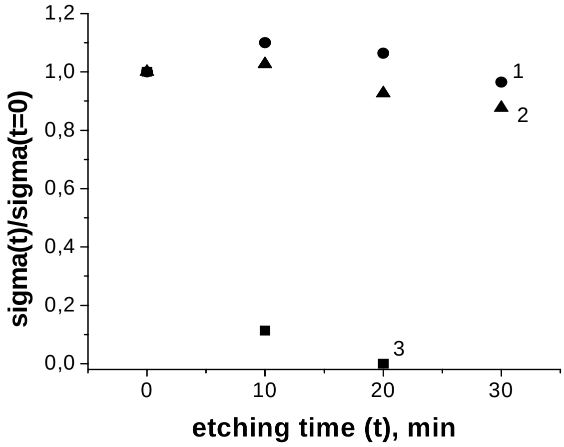


Fig.4. Conductivity dependence on the etching time for samples № 54 at T=300K (symbol 1) и T=77K (2) and № 401 (3) at T=300K.

The influence of surface morphology on the electron characteristics of porous samples is demonstrated by the results of the electrophysical measurements. Transport properties of single crystal and porous InGaAs layers were studied by Van-der-Pay methods within the temperature range from 300 to 77 K. These measurements confirm the SPM data on the above- mentioned possibility of formation of an inhomogeneous network of quantum wires. From the temperature dependences for conductivity and electron mobility we can see that both conductivity of porous layer and electron mobility in two- dimensional network are very different from those in the single crystal. This fact is accounted for by a smaller role of the phonon scattering mechanism as compared with electron scattering on potential fluctuations and on surface defects in a porous layer. Some increase in the conductivity at the beginning of the electrolytic etch (Fig.4) is connected with the increase in the electron concentration as a result of its strong dependence on the surface characteristics of the sample. Further etching of a sample causes an appearance of disconnected single islands or arrays of nano-islands on the isolating substrate and thus a possible manifestation of different percolation effects in the longitudinal conductivity. This situation was observed in structure № 401 (Fig.4). Electrons in the monocrystalline InAlAs/InGaAs/InAlAs sample have the mobility at 300K to 4497cm/Vs and the conductivity to $1.17*10^{-2}$ $Ом^{-1}$. After 10 minutes of etching the electron mobility became 2082 cm/Vs, the conductivity - $1.32*10^{-3}$ $Ом^{-1}$. Etching of sample during 20 minutes makes the transport of charge carriers no longer observable, due to the absence of interconnection between different islands in the system (Fig.2).

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