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INVESTIGATION OF NANOSTRUCTURED SILICON SURFACES USING FRACTAL ANALYSIS

Fractal analysis was applied to images of nanostructured silicon surfaces which were acquired with a scanning electron microscope. A fractal model describing nanostructured silicon surfaces morphology is elaborated. It were obtained the numerical results for the fractal dimensions for 2 samples with different nanostructured shapes.

INTRODUCTION

Silicon is the dominant material of microelectronics industry. But the serious drawback of silicon is the limitation in optoelectronic applications i. e. produced non-radiative transition. After the discovery of visible photoluminescence (PL) from porous silicon (PS) an intensive research efforts has been taken towards the study of nanostructured silicon. Porous silicon consists of a network of nanometer size silicon crystallites in the form of nano-wires and nano-dots. Porous silicon structures has good mechanical robustness, chemical stability and compatibility with existing silicon technology so it has a wide area of potential applications such as waveguides, 1D photonic crystals, chemical sensors, biological sensors, photovoltaic devices etc [1].

In recent years, fractal geometry has been used to characterize the irregular forms of fractured materials. The fracture surface features are determined by the properties of the materials and also by the initial flaw defect sizes and stress states. Fractal objects are characterized by their fractal dimension, D, which is the dimension in which the proper measurement of a fractal object is made. Fractal dimension can be used as a diagnostic parameter characterizing the structure and mechanical properties of the surface layer. Tribological and elastic properties of the surface correlated with the fractal dimension: in areas with high fractal dimension the maximum friction and elasticity of the material is minimal. Also, by modifying the silicon surface by etching the surface, accompanied by an increase in fractal may by an order to increase the sensitivity of sensors based on nanostructured silicon [2, 3]. Therefore, in order to better understand a particular physical process occurring within nanostructured silicon, it is necessary to have detailed knowledge of the internal geometry and topology of the internal pore network. However, the surface area and pore size distribution alone do not meet all requirements to describe the characteristics of the nanostructured of silicon [4—5].

In this article, we review the topological features of nanostructured Si surfaces with two distinctive nanostructures, i. e. nanoislands and roughened shape, obtained by the deformation method [6]. The topological features of silicon surfaces are expressed in terms of the fractal concepts. In this study, we calculated the fractal dimension of the surface by box-counting method.

RESULTS AND DISCUSSION

As a result of high-temperature oxidizing of silicon, and also of some additional reasons, in near-surface layers the complex defect region which consists of disordered silicon and a layer containing dislocation networks is formed [6]. The depth of this defective layer is spread from the interface into the silicon to 10—20 microns. The given defect structure is formed owing to excess of mechanical stresses magnitudes of a threshold of plasticity. Is well known, that intensity of selective chemical etching depends on presence of initial defect structure, prestress processing and orientation of a surface. Etching away of silicon dioxide and treatment by various selective etching agents (Sacco, Sirtl, KOH solution, NaOH solution) surfaces allows to form nanostructures of silicon. It looks like short distance nanoislands of approximately the same size (Fig. 1) or roughened silicon surfaces (Fig. 2). The sizes and the shape of nanostructured silicon depend both on a chemical compound and etching conditions, and from initiating defect structure of near-surface silicon layers. Besides, the given defect structure directly depends on original plastic deformations [7].

As was mentioned above, the box-counting method is used to calculate the fractal dimension of the profile, and the fractal dimension of the surface can be calculated from the dimensions of its profile by adding units. Usually profile prepared by dissecting the test surface and the plane (the direction of fast scan).

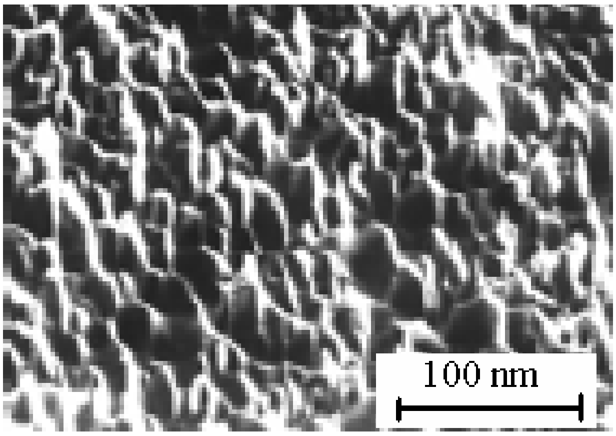

Fig. 1. SEM pattern of nanostructured silicon surface *(sample 1)*

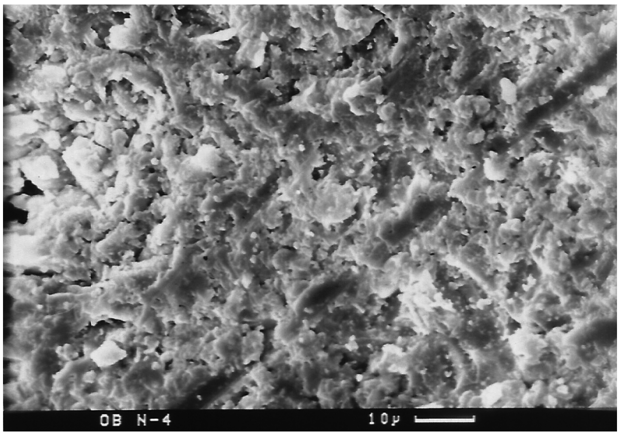

Fig. 2. SEM pattern of roughened silicon surface *(sample 2)*

To improve the accuracy of calculations can also use the modified the box-counting method, it combines this one and the "lake" algorithm, or method of the perimeter — area (area-perimeter method). Using this method, the surface is cut plane at a fixed level; for example, you can choose the level of:

$$Z_0 = (Z_{min} + Z_{max})/2, \tag{1}$$

where Z_{min}, Z_{max} — minimum and maximum heights of the points, respectively.

Intersection of the surface with this plane represents a set of closed lines, called "lake". The perimeter of each "lake" is linked to its area ratio:

$$L(S) = \beta F_d A^{(F_d - 1)/2}, \tag{2}$$

where β — constant, F_d — fractal dimension of the line, S — unit of length. Can also be seen in all sections of the "lake" from Z_{min} up to Z_{max}. "Lake" formed at the higher level sections, isolated portions of the surface close to the tops of the grains, the terms of the atoms close to the position of atoms in a single crystal, so the value of fractal dimension close to 2.0. The lower section of isolated regions, which lie at the grain boundaries, where the positions of atoms are arranged like an amorphous material, so the fractal dimension increases. Thus, the fractal dimension is calculated on the expression (2) the slope of the logarithm of the perimeter to the logarithm of the cross-sectional area of the grains. When using the modified method of counting cells (boxes) produce section of the surface plane (1) and get a set of simply connected domains on which to apply the usual method of counting cells. All topograph of the surface under study is filled with square cells with side and count the number of nonempty cells. With a decrease in cell size over non-empty cells are counted. Thus determines the dependence of the number of nonempty cells on their size. The fractal dimension is calculated from the slope depends on a double logarithmic scale [8].

The method was implemented in a software environment Matlab: the processing of the original images (Fig. 1, 2) searches boundaries differential contrast using Canny algorithm, i.e. introduced the following model swings: drop step type (the presence of the interface contrast) was determined by the Heaviside function, white noise at the boundary was set using a Gaussian distribution (Fig. 3). To determine the boundaries were marked with three criteria: the high detection probability drop, the high precision localization of the interface, the unique-

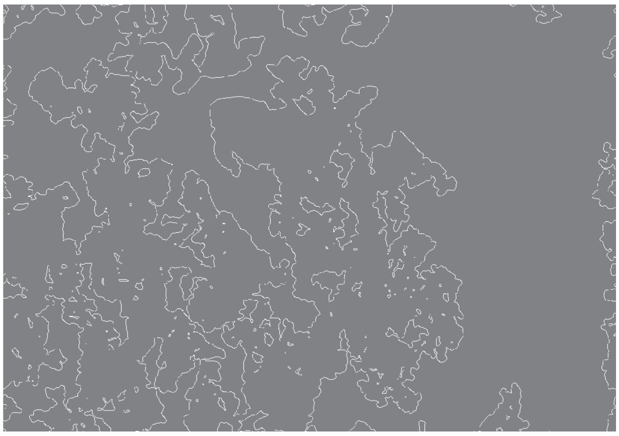

Fig. 3. Convert images to the original surface by Canny algorithm

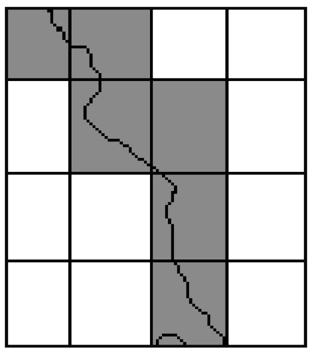

Fig. 4. Model filling in the processed image cells ($N = 16$, $N(S) = 6$)

ness of the existence of the contrast difference. It should be noted that the correct detection of the boundaries is very important because error in determining affects the value of fractal dimension, in most cases in the first decimal place. On the resulting image (Fig. 3) impose a grid of square cells with a given size. Then we count the cells through which the boundary lies $N(S)$ (Fig. 4). With decreasing cell size calculation was performed again.

The fractal dimension determined from the slope of the curve depending on a double logarithmic scale (Fig. 5) as follows:

$$D = \frac{\log N}{\log N(S)}. \qquad (3)$$

On figures 5, 6 show plots for samples.

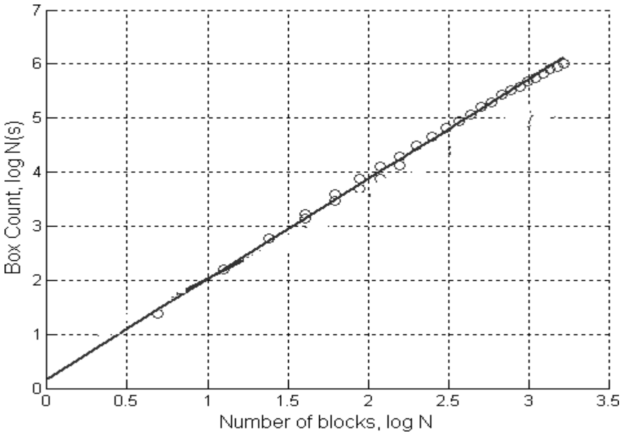

Fig. 5. Calculation of fractal dimension *(sample 1)*

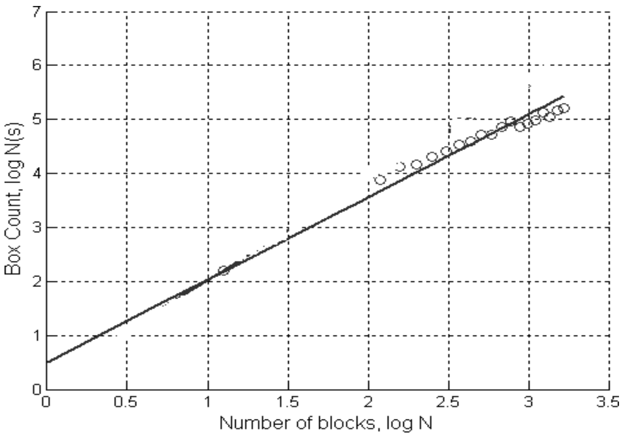

Fig. 6. Calculation of fractal dimension *(sample 2)*

Numerical results for the fractal dimension are presented in the Table:

Sample	Fractal dimension *D*
Sample 1	2.53
Sample 2	2.87

CONCLUSIONS

Thus, we can draw following conclusions. In near-surface layers of Si in Si-SiO_2 system the complex defect region which consists of disordered silicon and a layer containing dislocation networks is formed under high-temperature oxidization. After additional chemical treatment it were obtained nanostructured surface with different shapes of silicon. We have studied nanostructured silicon surfaces based on fractal concepts. Our adaptation of the box-counting method for fractal analysis was shown to be effective in accurately extracting the fractal dimension from experimental SEM data on Si surfaces. It were obtained the numerical results for the fractal dimensions for 2 samples with different nanostructured shapes.

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Key words: nanostructured silicon, fractal analysis.

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ИССЛЕДОВАНИЕ НАНОСТРУКТУРИРОВАННОЙ ПОВЕРХНОСТИ КРЕМНИЯ МЕТОДАМИ ФРАКТАЛЬНОГО АНАЛИЗА

Резюме

Фрактальный анализ был применен для исследования электронных изображений наноструктурированных поверхностей кремния, определения их морфологических особенностей. Были получены значения фрактальной размерности для двух образцов с различной формой наноструктурирования.

Ключевые слова: наноструктурированный кремний, фрактальный анализ.

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ДОСЛІДЖЕННЯ НАНОСТРУКТУРОВАНОЇ ПОВЕРХНІ КРЕМНІЮ МЕТОДАМИ ФРАКТАЛЬНОГО АНАЛІЗУ

Резюме

Фрактальний аналіз був застосований для дослідження електронних зображень наноструктурованих поверхонь кремнію, визначення їх морфологічних особливостей. Були отримані значення фрактальної розмірності для двох зразків з різною формою наноструктурування.

Ключові слова: наноструктурований кремній, фрактальний аналіз.