Medical applications of porous silicon

E M Loginova¹, D A Shishkina¹ and M A Zhuravleva²

¹Department of Electronics and Instrument Engineering, Samara University, Samara 443086, Russia
²Department of Biology, Samara University, Samara 443086, Russia

Abstract. Materials based on porous silicon are extremely attractive for biomedical applications due to their simple and flexible production, biocompatibility, biodegradability, controlled morphology, and multiple ways of introducing the drug into the body. This paper presents the results of studies of porous structures with a broad spectrum antibiotic ceftriaxone. It has been shown that the characteristics of the porous structure change upon saturation of the pores with the drug. It was shown that solutions of porous silicon + ceftriaxone have a characteristic peak at a wavelength of 1070 nm with increasing sonication time.

1. Introduction

Silicon is a component of all cells of the human body, its average daily consumption is about 20-50 mg. Depending on the degree of porosity, silicon particles can be biologically active, bioinert or biodegradable [1]. Currently, the possibility of using porous silicon powders as materials for nanocontainers for transporting drugs is being actively studied. It is possible to regulate the rate of release of the drug and the rate of resorption of the container in the body by controlling the development of the surface and porosity [2]. Porous silicon is an extremely attractive candidate for nanomedicine due to its interesting properties: 1) the process of making porous silicon is simple; 2) hydrophobic drugs with low solubility in a biological medium can be loaded into the pores of porous silicon particles after dissolution in an organic solvent; 3) the large surface area and the widely adaptable surface composition of the porous silicon carriers contribute to a high drug loading [3]; 4) retention of drug molecules in the pores to prevent crystallization; 5) high drug loading (up to 60% by weight) and concentration (up to 400 times); 6) surface chemistry for attaching target groups to porous silicon particles deliver playloads to diseased organs [4]. High interest is the absorption capacity of porous silicon, which allows it to be used for the treatment of cancer [5]. Porous silicon particles are capable of protecting sensitive proteins from degradation and enzymatic denaturation in stomach [6].

The main goal of drug delivery systems based on nanocontainers is the selective effect of the loaded drug on the focus of the disease with minimal side effects and toxicity associated with the distribution of the drug throughout the body during normal administration. Now the concept of nanomedicine has gone further, the direction of combining a therapeutic and diagnostic agent into a single delivery system is developing. Thus, many opportunities open up not only in the treatment of diseases, but also in early diagnosis and understanding of the biological response to certain treatments [7]. Porous silicon nanoparticles can also act as time-synchronized imaging tools by exploiting the optoelectronic properties of porous silicon [8-10].

It was determined that orthosilicic acid, which is a breakdown product of porous silicon, is readily absorbed in the gastrointestinal tract and subsequently excreted through the urinary system. Orthosilicic acid is also associated with homeostasis and regulation of key body processes such as...
collagen synthesis, prevention of atherosclerosis, Alzheimer's disease, maintenance of bone health, and improvement of the immune system [11].

The ability of porous silicon to support cell growth [12] enables ex-vivo tissue and organ regeneration [13] with further potential for the growth of the patient's own skin for subsequent autotransplantation or the use of donor cells for allotransplantation on burns or other serious wounds.

2. Experiment

Pretreatment of samples of silicon substrates was carried out in order to clean them from organic contaminants to ensure the uniformity of the etching process. For this, a solution of ammonium-ammonia peroxide was prepared in following proportions H$_2$O$_2$:NH$_4$OH:H$_2$O 1:1:4. Samples were immersed in a boiling solution for 7 minutes, then dipped in three waters.

19 samples of porous silicon were prepared by the electrochemical method in a horizontal cell [14] in an alcoholic solution of hydrofluoric acid in the ratio HF: C$_2$H$_5$OH 1: 1. The current density was $j = 30$ mA/cm$^2$, the etching time was 20 minutes. After etching, the samples were washed in distilled water and dried on filter paper.

To determine the porosity, a semi-destructive gravimetric method was used [15], which included sequential weighing of the samples before etching, after etching. To evaluate the obtained nanostructures, some of the samples were examined with a NEOPHOT 21 photomicroscope. Pieces were cut off with a scalpel and their cleavage was examined to determine the thickness to tell if it corresponded to the average thickness of the nanostructured substrates. The spectral characteristics of the absorption coefficient were studied using a Shimadzu UV-2450 spectrophotometer in the wavelength range from 190 to 1100 nm. The scanning speed is slow, the slit width is 5 nm.

3. Results

Figure 1 shows a cleavage of a sample with porous silicon. Under these conditions, the thickness of the porous layer was 50 μm.

![Figure 1. Image of the cleavage obtained with an optical microscope](image)

Porosity was determined by the formula:

$$P = \frac{m_1-m_2}{\rho \cdot S \cdot d} \cdot 100\%,$$

(1)
there \( m_1 \) – mass of the silicon sample before anodizing, \( m_2 \) – mass of the sample after anodizing, \( \rho \) – density of silicon, \( S \) – area of the porous layer, \( d \) – thickness of the porous layer.

Table 1 shows the results of determining the porosity of the samples.

| №  | \( m_1 \) (g) | \( m_2 \) (g) | \( \Delta m \) (g) | \( d \) (\( \mu \)m) | \( S \), cm\(^2\) | \( P \) (%) |
|----|---------------|---------------|-----------------|----------------|---------------|-----------|
| 1  | 0.5666        | 0.5480        | 0.0186          | 49.65          | 3.8           | 42.31     |
| 2  | 0.5045        | 0.4868        | 0.0177          | 48.94          | 40.26         |
| 3  | 0.6058        | 0.5870        | 0.0188          | 50.32          | 42.76         |
| 4  | 0.7817        | 0.7622        | 0.0195          | 52.06          | 44.35         |
| 5  | 0.5997        | 0.5799        | 0.0198          | 51.44          | 45.04         |

Under these etching modes, the porosity of the structures varied from 40 to 45%. Further, some of the porous silicon samples were saturated with a broad-spectrum antibiotic ceftriaxone (Table 2).

| №  | Weight to saturation (g) | Weight after saturation (g) |
|----|--------------------------|-----------------------------|
| 1  | 0.5453                   | 0.5720                      |
| 2  | 0.4441                   | 0.4585                      |
| 3  | 0.2708                   | 0.3019                      |
| 4  | 0.5936                   | 0.6245                      |
| 5  | 0.5524                   | 0.5807                      |
| 6  | 0.5843                   | 0.6004                      |

Table 2 shows that after saturation with ceftriaxone, the weights of the porous silicon samples increased. To confirm the presence of ceftriaxone in the pores, the volt-ampere characteristics of the samples were examined before and after the application of the drug (Figure 2).

![Figure 2. Volt-ampere characteristics of the samples.](image)

As can be seen from Figure 2, after saturation of porous silicon with ceftriaxone, the current-voltage characteristic changes, which confirms the filling of pores.
Then, porous silicon with Ceftriaxone was removed from the surface to create colloidal solutions and dissolved in 2 ml of water. Then 5 samples of the dissolved substance were subjected to grinding in an ultrasonic bath for 5, 10, 20, 30 and 35 minutes. A drug-free porous silicon solution was used as a control.

![Figure 3. Samples grinded in the ultrasonic bath.](image)

Figure 4 shows the spectral dependences of the absorption coefficient of aqueous solutions of porous silicon with Ceftriaxone.

![Figure 4. Absorption spectra of aqueous solutions of porous silicon with ceftriaxone.](image)

![Figure 5. Absorption spectra of dried porous silicon samples with ceftriaxone.](image)
Since Ceftriaxone was diluted with water, the effect of the latter on the spectra was very significant. Therefore, drops of solutions were applied to a glass slide and dried for 2 days to obtain a dry silicon powder with an antibiotic in its pores (Figure 5).

A noticeable absorption peak can be seen at 340 nm, which increases with increasing sonication time on the sample. This is due to a decrease in the particle size of porous silicon with the drug and a more thorough mixing of the solution.

4. Conclusion
Thus, as a result of the work by the method of electrochemical etching, porous structures with a porosity of the order of 40-45% were obtained. When ceftriaxone enters the pores, the characteristics of porous silicon change. The size of the nanocontainer affects the absorption spectrum of an aqueous solution of porous silicon with ceftriaxone. The possibility of using porous silicon nanoparticles as a means of targeted delivery of drugs of various pharmacological actions has been shown.

Acknowledgments
This work was supported by the Foundation for Assistance to Small Innovative Enterprises, grant № 12980GU/2018.

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