

## Physical materials technology

Original article

UDC 54.057

DOI: <https://doi.org/10.18721/JPM.19309>

### **POROSITY CHARACTERISTICS OF ULTRA-HIGH SPECIFIC SURFACE AREA SILICA PARTICLES AT FORMATION STAGES**

**Z. S. Balysh, D. V. Volodina, S. A. Grudinkin, D. A. Eurov,  
D. A. Kurdyukov, N. V. Glebova, E. Yu. Stovpiaga** 

Ioffe Institute, St. Petersburg, Russia

 [kattrof@gvg.ioffe.ru](mailto:kattrof@gvg.ioffe.ru)

**Abstract.** Spherical micro-mesoporous submicron particles of amorphous silica with a specific surface area (SSA) up to 2050 m<sup>2</sup>/g, comparable with that of nanoporous carbon materials, have been synthesized. Particle structure and chemical composition variations were studied by the adsorption porosimetry, thermogravimetric analysis and IR spectroscopy methods at formation stages. Sequential elimination of various organic porogens forming the particles' structure by washing and annealing in different ambients leading to pore opening and corresponding SSA growth were demonstrated. The distinctive feature of the developed post-treatment procedure is the stabilization of the fragile silica backbone due to the formation of a distributed network of surface silanol groups that maintain the achieved characteristics of high porosity.

**Keywords:** spherical particles, silica, micropores, mesopores, ultra-high specific surface area

**Funding:** This work was funded by the Russian Science Foundation, project No. 25-23-00189.

**For citation:** Balysh Z. S., Volodina D. V., Grudinkin S. A., Eurov D. A., Kurdyukov D. A., Glebova N. V., Stovpiaga E. Yu., Porosity characteristics of ultra-high specific surface area silica particles at formation stages, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 19 (3) (2026) 116–124. DOI: <https://doi.org/10.18721/JPM.19309>

This is an open access article under the CC BY-NC 4.0 license (<https://creativecommons.org/licenses/by-nc/4.0/>)

Научная статья

УДК 54.057

DOI: <https://doi.org/10.18721/JPM.19309>

### **ХАРАКТЕРИСТИКИ ПОРИСТОСТИ ЧАСТИЦ КРЕМНЕЗЕМА СО СВЕРХВЫСОКОЙ УДЕЛЬНОЙ ПОВЕРХНОСТЬЮ НА ЭТАПАХ ФОРМИРОВАНИЯ**

**З. С. Балыш, Д. В. Володина, С. А. Грудинкин, Д. А. Еуров,  
Д. А. Курдюков, Н. В. Глебова, Е. Ю. Стовпяга** 

Физико-технический институт имени А. Ф. Иоффе РАН, Санкт-Петербург, Россия

 [kattrof@gvg.ioffe.ru](mailto:kattrof@gvg.ioffe.ru)

**Аннотация.** Синтезированы сферические микромезопористые частицы аморфного кремнезема, имеющие удельную поверхность пор до 2050 м<sup>2</sup>/г. Методами адсорбционной порометрии, термогравиметрического анализа и инфракрасной спектроскопии исследованы изменения структуры частиц и их химического состава на этапах формирования. Показано постепенное исключение из структуры частиц различных органических по- рообразующих веществ, приводящее к открытию пор и соответствующему увеличению удельной поверхности материала в процессе отмывки и отжига в различных средах.



Отличительной особенностью процедуры постсинтетической обработки является стабилизация хрупкого кремнеземного каркаса за счет взаимодействия поверхностных силанольных групп, сохраняющая достигнутые рекордные характеристики пористости.

**Ключевые слова:** сферическая частица, кремнезем, микропоры, мезопоры, сверхвысокая удельная поверхность

**Финансирование:** Работа выполнена за счет гранта Российского научного фонда № 25-23-00189.

**Для цитирования:** Балыш З. С., Володина Д. В., Грудинкин С. А., Еуров Д. А., Курдюков Д. А., Глебова Н. В., Стовпяга Е. Ю. Характеристики пористости частиц кремнезема со сверхвысокой удельной поверхностью на этапах формирования // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2026. Т. 19. № 3. С. 116–124. DOI: <https://doi.org/10.18721/JPM.19309>

Статья открытого доступа, распространяемая по лицензии CC BY-NC 4.0 (<https://creativecommons.org/licenses/by-nc/4.0/>)

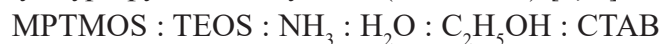
## Introduction

Recently, there has been strong interest in developing porous materials with high specific surface area (SSA). The largest SSA values (typically 1200 – 2300 m<sup>2</sup>/g) are observed in nanoporous carbons having subnanometer pores [1]. Nanoporous carbon materials are extensively used in, e.g., hydrogen storage devices, Li-ion batteries, and catalysts. However, numerous chemical processes (e.g., catalytic purification of vehicle exhaust gases) require incombustible supports. In particular, these are synthetic zeolites with an SSA of 400 – 600 m<sup>2</sup>/g [2] and mesoporous silicas (M41S family, SBA, etc.) with an SSA of up to 1200 m<sup>2</sup>/g [3].

The goal of our study was to obtain high-SSA submicrometer spherical particles of MCM-41 type silica. The large values of SSA (up to 2050 m<sup>2</sup>/g) are obtained by addition of various organosilanes and pore-forming substances to the reaction mixture, which act like soft templates and resulted in a formation of an interconnected system of micro- and mesopores within the particles. To determine the composition and structure of the high-SSA particles IR spectroscopy and thermogravimetric analysis (TGA) were used. A post-synthetic modification technique was developed comprising washing and annealing stages to stabilize the fragile silica backbone by formation of a distributed network of surface silanol groups and preserve the achieved high porosity characteristics. We believe that the obtained material, which combines all the benefits of silica (hydrophilicity, large number of functional groups, thermal and chemical stability) with a huge specific surface area comparable with that in nanoporous carbon will have significant impact for the processes, where the effectiveness of the materials used directly depends on the extent of available surface and the number of active centers, such as catalysis, sorption, separation.

## Experimental

The high-SSA SiO<sub>2</sub> particles were obtained in a water-ethanol-ammonia mixture containing dissolved cetyltrimethylammonium bromide (CTAB) by joint hydrolysis of tetraethoxysilane (TEOS) and 3-methacryloxypropyltrimethoxysilane (MPTMOS) [4, 5]. The reagents



were taken in molar ratio of 1 : 3 : 240 : 3120 : 1250 : 0.4, respectively. TEOS+MPTMOS were introduced 10 min after the beginning of a vigorous stirring of the rest of the components. The temperature of the reaction mixture was 42°C. The synthesis of particles was carried out for 5 hrs. under stirring at 200 r.p.m. The as-synthesized particles were treated as follows:

**Option No. 1.** The particles were washed once in the ethanolic solution (0.01 M) of HCl at a temperature of 70°C for 2 hrs. Then the material was annealed at 350°C in air for 2 hrs.

**Option No. 2.** The particles were washed in the ethanolic solution (0.01 M) of HCl at a temperature of 70°C for 2 hrs. Then they were collected by centrifugation and washed once more at the above conditions. The washed particles were dried at ambient conditions.

**Option No. 3.** The particles were washed twice in the ethanolic solution (0.01 M) of HCl at a temperature of 70°C as described above (Variant No. 2). Then the resulting material was annealed at 350°C in air for 2 hrs.

**Option No. 4.** The particles were washed twice in the ethanolic solution (0.01 M) of HCl at a temperature of 70°C as described in Variant No. 2. Then the particles were preliminary annealed at 350°C in air for 2 hrs. After that the final annealing at 430 °C in air for 5 hrs. was carried out.

**Option No. 5.** The particles were washed twice in the ethanolic solution (0.01 M) of HCl at a temperature of 70°C as described in Variant No. 2. Then the particles were preliminary annealed at 350°C in air for 2 hrs. After that the final annealing at 430 °C in a flow of oxygen for 5 hrs. was carried out. The oxygen supply system was equipped with a U-tube filled with bidistilled deionized water. As a result, the gas supplied to the reactor contained water vapor ( $H_2O$  content  $\sim 20$  g/m<sup>3</sup>).

The adsorption structural analysis was carried out on a 3FLEX analyzer (Micromeritics, USA) with the use of gaseous nitrogen and argon as adsorbates at 77 K. SSA, pore volume and pore size distribution (PSD) were calculated using the built-in software of the analyzer. At 77 K, nitrogen has a saturation pressure of 760 Torr, whereas argon has the one of 200 Torr. The Brunauer – Emmet – Teller (BET) SSA value for  $N_2$  isotherms was determined in the relative pressure range between 0.06 and 0.20. This range provided a correlation coefficient of at least 0.999. In the case of Ar isotherms, the “standard” relative pressure range for BET (0.05–0.30) was chosen, since a correlation coefficient above 0.99 could not be achieved. The total pore volume  $V_p$  of samples was determined at the relative pressure  $P/P_0 \rightarrow 0.991$ . An analysis of SSA, pore volume and pore size distribution was also carried out by the NLDFT method [6] for pillared clay in the case of  $N_2$  adsorption branch and for Ar77@Zeolite, H-Form in the case of Ar adsorption branch. The model was chosen in such a way that the minimum value of RMS error ( $< 4$  cm<sup>3</sup>/g) was achieved. Non-negative regularization values were 0.3 and 0.2 for  $N_2$  and Ar isotherms, correspondingly.

Thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) study were performed using a TGA/DSC1 analyzer (Mettler-Toledo, Switzerland) with a heating rate 10 °C/min. FTIR spectra were measured using an IFS 113v spectrometer (Bruker, USA).

## Results and discussion

The goal of the post-synthetic treatment was mild organic removal, to form pores in place of organic groups and prevent polycondensation or other damage of the silica framework, but rather to stabilize it. Removal of organics was carried out in three stages: washing, pre-annealing and final annealing. Most of the CTAB was removed on the first stage involving washing the particles in an alcoholic solution (0.01 M) of HCl at 70°C (see Figs.1, 2).

Then, a preliminary annealing was carried out at 350°C in air. At the final stage, the particles were annealed at 430°C in a flow of oxygen containing saturated water vapor. The post-synthetic treatment of the particles under the above-described conditions provided the formation of silica with the maximum BET SSA (see Fig. 3 and Table). The obtained particles had submicron size (their average diameter was 450 nm) and spherical shape (see inset in Fig.4, b).

According to FTIR results, at different stages of post-synthetic treatment of particles (washing, annealing) various organic moieties were gradually removed [7 – 9], which was accompanied with an increase in the amount of adsorbed water and silanol groups. The as-synthesized silica particles contain various associates of CTA and MP groups (see curve 1 in Fig. 1). Along with the vibrational mode's characteristic of silica [7], there are bands corresponding to vibrations of  $N-CH_3$  groups (characteristic of CTAB [8]),  $C-O$ ,  $C=O$  and  $C=C$  groups (present in MPTMOS [9]). After the washing step, the spectrum of particles (see curve 2 in Fig. 1) contains almost no bands corresponding to methylammonium ( $N-CH_3$ ) group vibrations in the CTAB molecule and the intensity of vibrational modes of methylene groups ( $-CH_2-$ ) prevailing in CTAB significantly decreases, which confirms almost complete removal of CTAB moieties from the particles. The presence of the bands corresponding to  $C-H$ ,  $-CH_2-$  and  $-CH_3$  vibrations is caused by that MPTMOS, which remains within particles after CTAB washing, contains these groups. A broad band at 3450 cm<sup>-1</sup> corresponding to  $-OH$  stretching vibrations in hydrogen-bound molecules of physically adsorbed water [7] becomes more pronounced indicating that some pores turn out to be accessible to water after CTAB elimination. After annealing of particles at 350°C in air, the bands corresponding to atomic vibrations in organic molecules almost completely disappeared

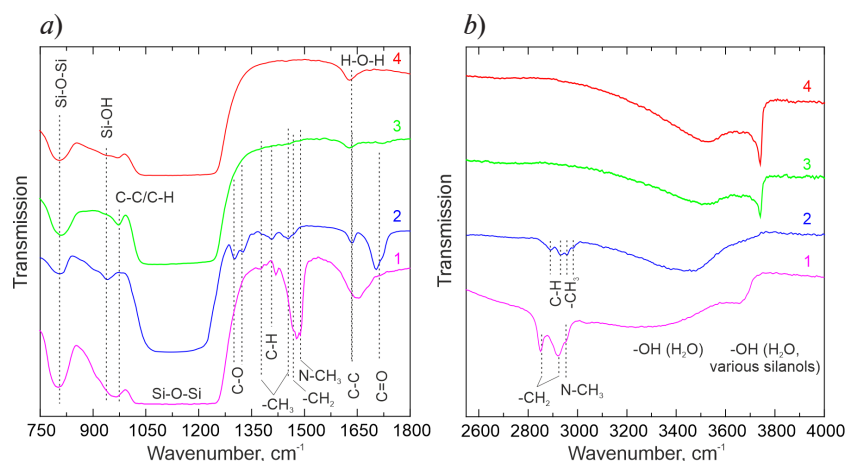


Fig. 1. FTIR spectra in the wavenumber ranges of  $750 - 1800 \text{ cm}^{-1}$  (a) and  $2575 - 4000 \text{ cm}^{-1}$  (b) for the high-SSA  $\text{SiO}_2$  particles just after synthesis (curves 1) and after different post-treatment routes (2 – 4): Option No. 2 (2), Option No. 3 (3), Option No. 5 (4). Characteristic bands are designated

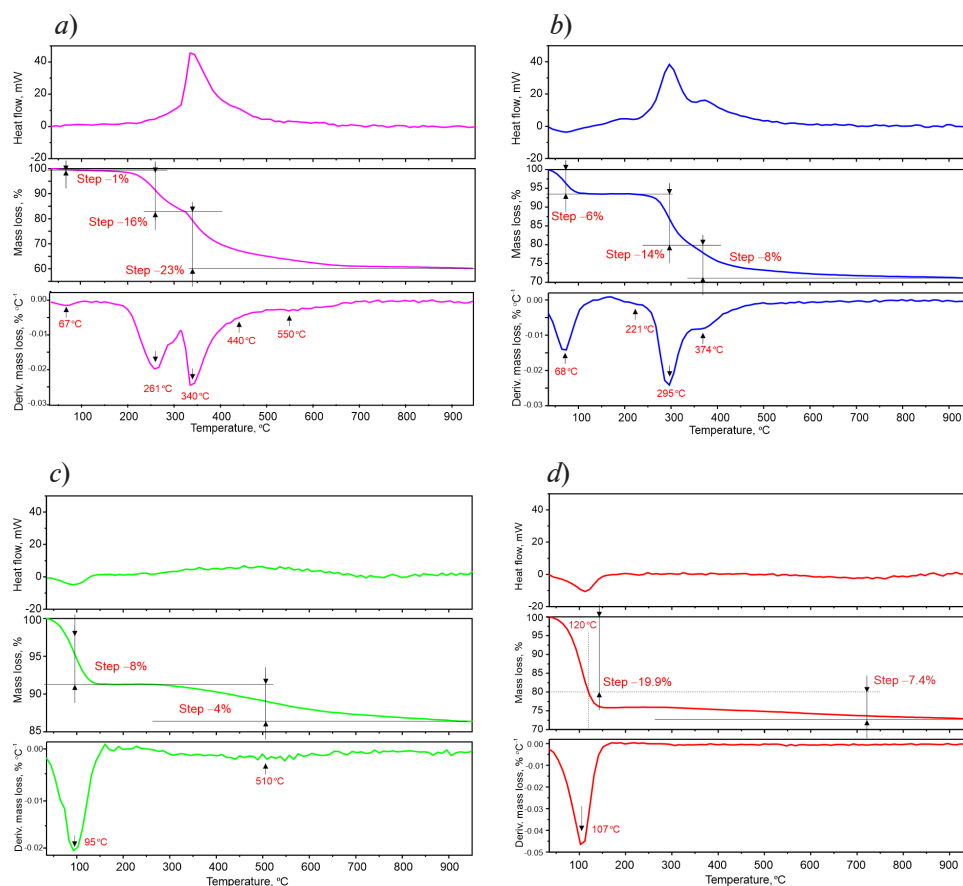


Fig. 2. DSC, TG and DT curves (from top to bottom in each panel) for the high-SSA  $\text{SiO}_2$  particles just after synthesis (a) and after different post-treatment routes (b – d): Option No. 2 (b); Option No. 3 (c); Option No. 5 (d).

Characteristic mass loss steps are marked.

(see curve 3 in Fig. 1). A broad band in the range  $3500 - 3800 \text{ cm}^{-1}$  appears, which corresponds to vibrations of various types of silanol groups. According to FTIR, the particles finally annealed in wet oxygen contain the largest number of single and geminal silanols and no organic groups (see curve 4 in Fig. 1).

There are features on DSC, TG and differential thermal (DT) curves of as-synthesized and washed particles (see Fig. 2, *a*, *b*) determined by thermal decomposition of CTA [10] and MP [11] groups, correspondingly. Note, that the as-synthesized particles contain almost no physically adsorbed water (see Fig. 2, *a*). Its content increases from stage to stage of post-synthetic treatment and reaches 20% of sample mass after final annealing in oxygen, which correlates with the FTIR results (see Fig. 1). Moreover, the temperature of the adsorbed water removal increases from 67 to 107°C (see Fig. 2, *b* – *d*), which is caused by the formation of hydrogen bonds between molecules of H<sub>2</sub>O and Si–OH groups. At the same time, the mass of organics gradually decreased and after preliminary annealing at 350°C its value became less than 4% (see Fig. 2, *c*) since the observed step in the temperature range of 300 – 950°C is associated not only with the oxidation of organics, but also with the removal of surface silanols (the contents of absorbed and chemically bonded water are presented in Table).

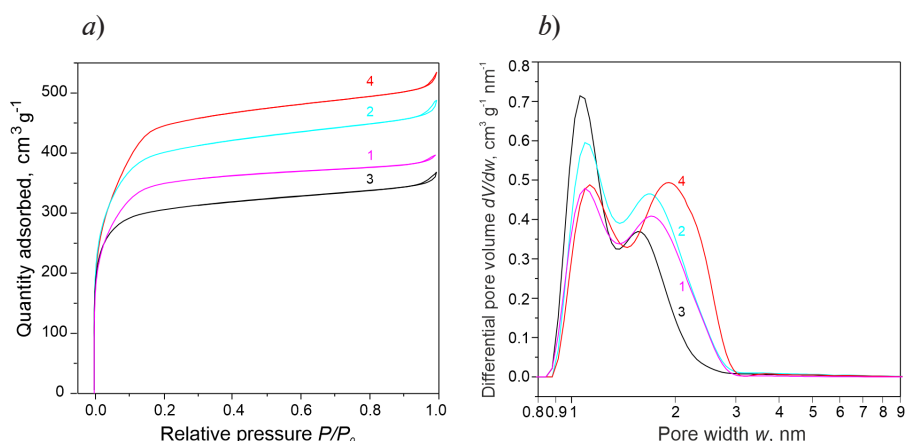


Fig. 3. Adsorption isotherms of gaseous N<sub>2</sub> (77 K) (*a*) and NLDFT PSD (*b*) for the high-SSA SiO<sub>2</sub> particles after different post-treatment procedures: Option No. 1 (curves 1); Option No. 3 (2); Option No. 4 (3); Option No. 5 (4)

Table

**Porosity characteristics of particles and the content of adsorbed and chemically bonded water at the different stages of organic removal**

| Posttreatment<br>(Option No.) | Adsorbate      | SSA, m²/g |      | $V_p$ , cm³/g (at $P/P_0 = 0.991$ ) | Physisorbed water<br>(TGA) |                        | OH group content<br>at 950°C (TGA) |          |
|-------------------------------|----------------|-----------|------|-------------------------------------|----------------------------|------------------------|------------------------------------|----------|
|                               |                | BET       | DFT  |                                     | mmol/g                     | H <sub>2</sub> O/(nm)² | mmol/g                             | OH/(nm)² |
| 1                             | N <sub>2</sub> | 1335      | 1423 | 0.61                                | —                          |                        |                                    |          |
| 3                             |                | 1516      | 1644 | 0.76                                | 4.4                        | 1.8                    | 4.4                                | 1.9      |
| 4                             |                | 1137      | 1382 | 0.57                                | —                          |                        |                                    |          |
| 5                             |                | 1713      | 1785 | 0.83                                | 11.1                       | 3.9                    | 8.2                                | 3.6      |
| 5                             | Ar             | 2057      | 2035 | 0.70                                | 11.1                       | 3.2                    | 8.2                                | 3.0      |

Notations:  $V_p$  is the total pore volume,  $P/P_0$  is the relative pressure; SSA is the Specific Surface Area, BET is the Brunauer – Emmet – Teller method; DFT is the Density Functional Theory; TGA is the thermogravimetric analysis. Footnote: The amount of sorbed water and the number of OH groups, in mmol/g, (see the 2 right columns of the Table) were determined from the TG curves by the value of mass loss in temperature ranges of 35 – 120°C and 120 – 950°C respectively.

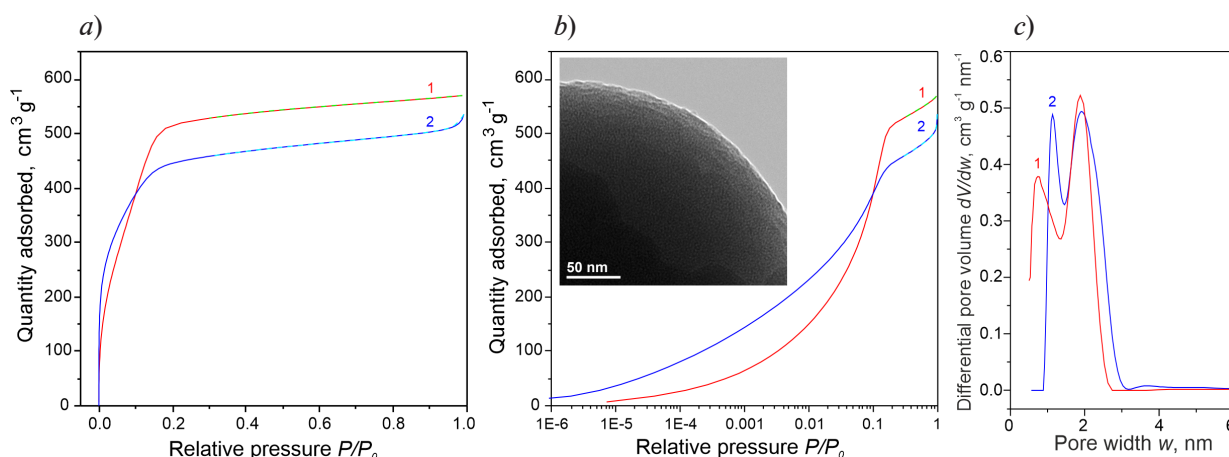


Fig. 4. Adsorption isotherms (77 K) in 2 scales: linear (a) and logarithmic (b), as well as NLDFT PSD (c) for the high-SSA  $\text{SiO}_2$  particles. Gaseous adsorbate used: Ar (1) and  $\text{N}_2$  (2).

*Inset: a micrograph of the particle*

The stepwise isotherms of  $\text{N}_2$  and Ar adsorption (see Fig. 3, a) belong to type IV [12] and are characteristic of M41S materials. The values of the SSA and pore volume of the particles are summarized in Table. Note, that two-fold washing leads to higher porosity, likely due to almost complete removal of CTAB molecules. This indicates that the temperature of the final annealing  $430^\circ\text{C}$  was optimal, lower temperatures would not have been able to provide a complete oxidation of all the organics (see Figs. 1, 2), while higher temperatures led to the sintering of the material and collapse of the pores. The composition of the gas mixture is also important. In particular, the final annealing at  $430^\circ\text{C}$  in air drastically decrease SSA value of the particles (see Fig. 3 and Table). The above-mentioned annealing without water possibly leads to a significant loss of hydroxyl (silanol) groups due to their polycondensation with the subsequent formation of  $-\text{Si}-\text{O}-\text{Si}-$  bonds. As a consequence, the pore walls became thicker and the porosity of the material decreased. The addition of saturated water vapor to oxygen during annealing was accompanied by a jump in the SSA values (see Fig. 4), which was caused by high content of surface silanols that came to replace the organics that stabilized the structure before. Taking the above into the account, the Option No. 5 of the post-treatment route is the optimal.

### Summary

Submicrometer spherical micro-mesoporous  $\text{SiO}_2$  particles with external diameter of 450 nm have been synthesized with a specific surface area of up to  $2050 \text{ m}^2/\text{g}$ , comparable with that of nanoporous carbon materials. The particles have two pore subsystems: micropores and mesopores with relatively broad size distributions and two pronounced maxima: at  $\sim 1.2$  and  $1.9 \text{ nm}$  respectively. We suggest that the smallest  $0.5 \text{ nm}$  micropores may be located inside the framework of silica-oxygen tetrahedra, what could explain such a large value of the specific surface area. The mild post-treatment procedure we developed included several washing and annealing stages and allowed forming the micro- and mesopores in the place of various organic groups, preventing polycondensation or other damage of the silica framework and its stabilization with surface silanol groups.

### Acknowledgments

The authors thank Dr. D. A. Kirilenko (Ioffe Institute), for transmission electron microscopy measurements.

The microscopic study was carried out on equipment of the Federal Joint Research Center "Material Science and Characterization in Advanced Technology".

## REFERENCES

1. Gogotsi Y., Presser V., Carbon nanomaterials, 2nd ed., CRC Press, Boca Raton, Florida, USA, 2013.
2. Breck D.W., Zeolite molecular sieves: structure, chemistry, and use. Wiley, 1973.
3. Zhao D., Wan Y., Zhou W., Ordered mesoporous materials, John Wiley & Sons, Inc., Hoboken, New Jersey (USA), 2013.
4. Mastaliev V. A., Neplokh V. V., Aybush A. V., et al., Nonlinear optical phenomena in mesoporous SiO<sub>2</sub> and Si/SiO<sub>2</sub> nanoparticles, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 17 (3.2) (2024) 207–211.
5. Eurov D. A., Kurdyukov D. A., Medvedev A. V., et al., Micro-mesoporous submicron silica particles with pore size tunable in a wide range: Synthesis, properties and prospects for LED manufacturing, Nanotechnol. 32 (21) (2021) 215604.
6. Olivier J. P., Occelli M. L., Surface area and microporosity of a pillared interlayered clay (PILC) from a hybrid density functional theory (DFT) method, J. Phys. Chem. B. 105B (22) (2001) 5358–5358.
7. Innocenzi P., Infrared spectroscopy of sol-gel derived silica-based films: A spectra-microstructure overview, J. Non-Cryst. Solids. 316 (2–3) (2003) 309–319.
8. Lin-Vien D., Colthup N. B., Fateley W. G., Grasselli J. G., The handbook of infrared and Raman characteristic frequencies of organic molecules, Academic Press, San Diego, California (USA), 1991.
9. Gutiérrez-Becerra A., Barcena-Soto M., Soto V., et al., Structure of reverse microemulsion-templated metal hexacyanoferrate nanoparticles, Nanoscale Res. Lett. 7 (20 Jan) (2012) 83.
10. Kleitz F., Schmidt W., Schüth F., Calcination behavior of different surfactant-templated mesostructured silica materials, Microporous Mesoporous Mater. 65 (1) (2003) 1–29.
11. Pellice S., Galliano P., Castro Y., Durán A., Hybrid sol-gel coatings produced from TEOS and  $\gamma$ -MPS, J. Sol-Gel Sci. Technol. 28 (1) (2003) 81–86.
12. Gregg S. J., Sing K. S. W., Adsorption, surface area and porosity. 2nd ed. Academic Press, London, 1982.

## СПИСОК ЛИТЕРАТУРЫ

1. Gogotsi Y., Presser V. Carbon nanomaterials. 2nd edition. Boca Raton, Florida (USA): CRC Press, 2013. 529 p.
2. Брек Д. Цеолитовые молекулярные сита. Пер. с англ. М.: Мир, 1976. 782 с.
3. Zhao D., Wan Y., Zhou W. Ordered mesoporous materials. Hoboken, New Jersey (USA): John Wiley & Sons, Inc., 2013. 523 p.
4. Mastaliev V. A., Neplokh V. V., Aybush A. V., et al., Nonlinear optical phenomena in mesoporous SiO<sub>2</sub> and Si/SiO<sub>2</sub> nanoparticles, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 2024. Vol. 17. No. 3.2. Pp. 207–211.
5. Eurov D. A., Kurdyukov D. A., Medvedev A. V., Kirilenko D. A., Tomkovich M. V., Golubev V. G. Micro-mesoporous submicron silica particles with pore size tunable in a wide range: synthesis, properties and prospects for LED manufacturing // Nanotechnology. 2021. Vol. 32. No. 21. P. 215604.
6. Olivier J. P., Occelli M. L. Surface area and microporosity of a pillared interlayered clay (PILC) from a hybrid density functional theory (DFT) method // The Journal of Physical Chemistry B. 2001. Vol. 105B. No. 22. Pp. 5358–5358.
7. Innocenzi P. Infrared spectroscopy of sol-gel derived silica-based films: a spectra-microstructure overview // Journal of Non-Crystalline Solids. 2003. Vol. 316. No. 2–3. Pp. 309–319.
8. Lin-Vien D., Colthup N. B., Fateley W. G., Grasselli J. G. The handbook of infrared and Raman characteristic frequencies of organic molecules. San Diego, California (USA): Academic Press, 1991. 503 p.
9. Gutiérrez-Becerra A., Barcena-Soto M., Soto V., Arellano-Ceja J., Casillas N., Prévost S., Noirez L., Gradzielski M., Escalante J. Structure of reverse microemulsion-templated metal hexacyanoferrate nanoparticles // Nanoscale Research Letters. 2012. Vol. 7. 20 January. P. 83.



10. Kleitz F., Schmidt W., Schüth F. Calcination behavior of different surfactant-templated mesostructured silica materials // Microporous and Mesoporous Materials. 2003. Vol. 65. No. 1. Pp. 1–29.
11. Pellice S., Galliano P., Castro Y., Durán A. Hybrid sol-gel coatings produced from TEOS and  $\gamma$ -MPS // Journal of Sol-Gel Science and Technology. 2003. Vol. 28. No. 1. Pp. 81–86.
12. Гпер С. Д. Адсорбция, удельная поверхность, пористость. Пер. с англ. М.: Мир, 1970. 407 с.

## THE AUTHORS

### **BALYSH Zoya S.**

*Ioffe Institute*

26 Politechnicheskaya St., St. Petersburg, 194021, Russia

balyshzoe@gmail.com

ORCID: 0009-0001-1698-9162

### **VOLODINA Daria V.**

*Ioffe Institute*

26 Politechnicheskaya St., St. Petersburg, 194021, Russia

dasha13129@gmail.com

ORCID: 0009-0009-4336-0712

### **GRUDINKIN Sergey A.**

*Ioffe Institute*

26 Politechnicheskaya St., St. Petersburg, 194021, Russia

grudink@gvg.ioffe.ru

ORCID: 0000-0003-1344-9483

### **EUROV Daniil A.**

*Ioffe Institute*

26 Politechnicheskaya St., St. Petersburg, 194021, Russia

edan@mail.ru

ORCID: 000-0002-7471-4028

### **KURDYUKOV Dmitry A.**

*Ioffe Institute*

26 Politechnicheskaya St., St. Petersburg, 194021, Russia

kurd@gvg.ioffe.ru

ORCID: 0000-0002-3041-9609

### **GLEBOVA Nadezhda V.**

*Ioffe Institute*

26 Politechnicheskaya St., St. Petersburg, 194021, Russia

Glebova@mail.ioffe.ru

ORCID: 0000-0003-4519-0111

### **STOVPIAGA Ekaterina Yu.**

*Ioffe Institute*

26 Politechnicheskaya St., St. Petersburg, 194021, Russia

kattrof@gvg.ioffe.ru

ORCID: 0000-0003-0434-5252

## СВЕДЕНИЯ ОБ АВТОРАХ

**БАЛЫШ Зоя Сергеевна** — лаборантка лаборатории физики аморфных полупроводников Физико-технического института имени А. Ф. Иоффе РАН, Санкт-Петербург, Россия.

194021, Россия, г. Санкт-Петербург, Политехническая ул., 26

balyshzoe@gmail.com

ORCID: 0009-0001-1698-9162

**ВОЛОДИНА Дарья Владимировна** — лаборантка лаборатории физики аморфных полупроводников Физико-технического института имени А. Ф. Иоффе РАН, Санкт-Петербург, Россия.

194021, Россия, г. Санкт-Петербург, Политехническая ул., 26

dasha13129@gmail.com

ORCID: 0009-0009-4336-0712

**ГРУДИНКИН Сергей Александрович** — кандидат физико-математических наук, старший научный сотрудник лаборатории физики аморфных полупроводников Физико-технического института имени А. Ф. Иоффе РАН, Санкт-Петербург, Россия.

194021, Россия, г. Санкт-Петербург, Политехническая ул., 26

grudink@gvg.ioffe.ru

ORCID: 0000-0003-1344-9483

**ЕУРОВ Даниил Александрович** — кандидат физико-математических наук, старший научный сотрудник лаборатории физики аморфных полупроводников Физико-технического института имени А. Ф. Иоффе РАН, Санкт-Петербург, Россия.

194021, Россия, г. Санкт-Петербург, Политехническая ул., 26

edan@mail.ru

ORCID: 0000-0002-7471-4028

**КУРДЮКОВ Дмитрий Александрович** — кандидат химических наук, ведущий научный сотрудник лаборатории физики аморфных полупроводников Физико-технического института имени А. Ф. Иоффе РАН, Санкт-Петербург, Россия.

194021, Россия, г. Санкт-Петербург, Политехническая ул., 26

kurd@gvg.ioffe.ru

ORCID: 0000-0002-3041-9609

**ГЛЕБОВА Надежда Викторовна** — кандидат физико-математических наук, старший научный сотрудник лаборатории мощных полупроводниковых приборов Физико-технического института имени А. Ф. Иоффе РАН, Санкт-Петербург, Россия.

194021, Россия, г. Санкт-Петербург, Политехническая ул., 26

Glebova@mail.ioffe.ru

ORCID: 0000-0003-4519-0111

**СТОВПЯГА Екатерина Юрьевна** — кандидат химических наук, заведующая лабораторией физики аморфных полупроводников Физико-технического института имени А. Ф. Иоффе РАН, Санкт-Петербург, Россия.

194021, Россия, г. Санкт-Петербург, Политехническая ул., 26

kattrof@gvg.ioffe.ru

ORCID: 0000-0003-0434-5252

*Received 17.02.2026. Approved after reviewing 21.04.2026. Accepted 21.04.2026.*

*Статья поступила в редакцию 17.02.2026. Одобрена после рецензирования 21.04.2026. Принята 21.04.2026.*