Review on Design, Synthesis, and Use of High Temperature Resistant Aerogels Exceeding 800 °C

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Abstract

As a type of ultra-light and super thermal insulation solid-state porous materials, aerogels have attracted increasing attention for aerospace, transportation, and building insulation applications. However, when aerogels are applied in these fields, resistance to high temperatures is a prerequisite for them. The most traditional silica aerogels can resist up to 600 °C, but their porous structures are destroyed at higher temperatures and no longer possess excellent thermal insulation capacity and low density. Though a significant number of new aerogels have been reported in the past two decades, the number of aerogels that could resist ultra-high temperatures, *e.g.*, >800 °C, is relatively few. Nevertheless, it's exciting to see that more and more aerogels that can resist temperatures higher than 1000 °C, and even up to 1500 °C, have been reported in the past few years. This paper gives an overview of aerogels that could resist more than 800 °C, and they defined as high-temperature resistant aerogels (HTRAs) in this review. The synthetic strategies, mechanisms, chemical compositions, and specific applications of the HTRAs will be reviewed and discussed. This paper would be a timely review to summarize the most recent progress in the HTRAs, and provide insights into the designing of various HTRAs.

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1. Introduction

Aerogels are well known for their low density (0.003 g/cm³), high porosity (99 %), large specific surface area (SSA) (1000 m²/g), and low thermal conductivity (0.010 W/mK). Consequently, aerogels have found wide applications in various fields such as thermal insulation, acoustic insulation, water purification, separation, catalyst, sensors, and biomedicine.^[1-10] Nevertheless, the use of aerogels in thermal insulation is the most attractive application due to their extremely low thermal conductivity and low density, both of which are the most attractive parameters in one material. Recent commercial applications of aerogels are also for thermal insulation purposes.^[11] Unlike the applications of

aerogels in biomedicine, energy, and water purification, when aerogels are used for thermal insulation, either in building or aerospace, they should be stable in extremely harsh conditions, *e.g.*, the temperatures are higher than 800 °C.^[12-15]

There is currently no unified definition of aerogel, and the concept has been continuously developed. The IUPAC definition of aerogel is a gel composed of microporous solids whose dispersed phase is gas.^[16] While various freeze-dried gels and ambient pressure-dried gels are also being considered as aerogels recently.^[17] The definition proposed by Du *et al.* that aerogel is a “state of matter” due to their qualitative differences in bulk properties, transitional density, and enthalpy between liquid and gas phases regardless of their chemical composition,^[18] gave a fresh overview of the field of aerogels.

Aerogels have been rapidly developed in the last two decades due to the significant progress in monomers, drying methods, and synthetic approaches (Fig. 1a). However, the progress in high temperature resistant aerogels (HTRAs) that can resist temperatures higher than 800 °C fall behind of other type of aerogels, and it became booming in the past five years (Fig. 1b).^[19] The chemical composition of aerogels had been gradually diversified after the first discovery of aerogel by Kistler in the 1930s.^[20] For instance, Teichner's group^[21] firstly

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Fig. 1 (a) Published literature in the development of aerogels; (b) Published literature on the development of HTRAs.

used tetramethoxyorthosilicate (TMOS) to prepare silica aerogels in 1968. Further, Russo *et al.*^[22] prepared silica aerogels using tetraethyloorthosilicate (TEOS) as monomer. This method was economical and efficient for the production of silica aerogels. Belido *et al.*^[23] obtained zirconia aerogels with high SSA using sol-gel transition and supercritical liquid drying (SCLD) method. Subsequently, Kanazidis *et al.*^[24] reported cluster bonding routes to prepare sulfur groups functionalized aerogels in 2007. These are all landmarks for the synthesis of HTRAs. Recently, the development of aerogels is much more diverse, such as new ceramic aerogels,^[25-27] graphene aerogels,^[28-30] MXene aerogels,^[31,32] and supramolecular polymeric aerogels,^[33-36] have been reported.

The development of HTRAs is limited by the difficulty of sol-gel technology. However, with the emergence of new technologies, new methods and new demands, HTRAs have received increasing attention. The main research directions of HTRAs are oxide aerogels, carbon aerogels, nitride aerogel and carbide aerogels.^[13] Among them, oxide aerogels (such as silicon oxide and alumina) are easy to shrink and sinter at high temperatures (800-1000 °C), exhibiting relative poor high-temperature resistance.^[37] Carbon aerogels perform well in an inert atmosphere or under the protection of antioxidant coatings at 2000-3000 °C, but oxidation occurs in the presence of oxygen above 350 °C, which affects the thermal insulation performance of the material.^[38] Although the surface oxidation of them can be suppressed to some extent by coating an antioxidant layer, the antioxidant layer is fragile for long-term usage, which limit the service life of carbon aerogels and their applications in high temperatures. Carbide aerogels (e.g. SiC aerogel) can maintain good mechanical strength and antioxidant properties above 1500 °C and have excellent insulation effects.^[39,40] Therefore, carbide aerogels have drawn great interest in their potential applications in high temperature insulation.

Thereafter, this review will give a timely overview on the development of HTRAs. It will focus on the mechanism of high temperature resistance, synthetic strategies toward the HTRAs, type of aerogels that can be ascribed to HTRAs, and the applications of the HTRAs. Finally, this review provides an outlook on the future research and development direction of HTRAs.

2. Mechanism of high temperature resistance

Aerogels are attractive thermal insulation materials under extreme conditions due to their low thermal conductivities, low densities, variable chemical compositions and physical structures. Generally, to design aerogels with high temperature resistance (HTR), two most significant requirements need to be taken into consideration, which are two critical factors and designing principles for HTR: (1) the thermal stability of the building blocks of aerogels should be high enough (it cannot be thermally degraded); and (2) crystal growth and phase transition of the building blocks must be prohibited even if they are not degraded at such high temperatures (the porous structures cannot be melted). The first requirement limits the choice of materials. For example, carbon materials cannot be used as precursors for HTRAs, such as graphene and carbon nanotubes (CNT), because they will undergo oxidative decomposition in an aerobic conditions at high temperatures.^[41,42] Polymers^[43-53] cannot be used as candidate precursors neither, although some aromatic heterocyclic polymers exhibit thermal stability in an oxygen-free thermal decomposition temperature up to 550 °C (e.g. polyimide aerogels and aramid aerogel).^[54-58] Since most of the ceramics^[59,60] are materials with extremely strong ionic bonds or covalent bonds, they have higher melting point, corrosion resistance, oxidation resistance, and heat resistance compared with metals and polymers. Accordingly, ceramics composed of oxides, nitrides, carbides, and their composites, which possess excellent fire/corrosion resistances are the best choices for the construction of HTRAs.

Fig. 2 (a) AISWF sol-gel process; (b) Schematic representation of the preparation of $\text{MO}_x-(\text{MO}_x/\text{SiO}_2)-\text{SiO}_2$ core-shell nanostructured metal oxide wet gels via ACLD; Photograph of typical pristine and core-shell nanostructured; (c) Al_2O_3 , (d) ZrO_2 , and (e) TiO_2 aerogels before and after heat treatment at high temperatures. (a-e Reproduced with the permission from [70], Copyright 2013 American Chemical Society), (f) Fabrication of the MFASs through the SIG-SCFD strategy (Reproduced with the permission from [68], Copyright, 2021 Elsevier B.V.)

Silica (SiO_2),^[27] alumina (Al_2O_3),^[60,61] and other types of metal oxides do not thermal degrade at temperature higher than 1000 °C. However, native SiO_2 aerogels and alumina aerogels could not be considered as HTRAs because they do not fulfill the second requirements. The porous structures of these aerogels could be significantly changed under high temperatures.^[62-68] Recently, crystal growth and phase transition of the building blocks have been successfully resolved via construction of a core-shell structure as illustrated in Fig. 2. Due to the presence of SiO_2 shell, the crystal growth of the metal oxide in the core was restricted, and the shrinkage of the aerogels was also limited. Thus, HTRAs of Al_2O_3 , ZrO_2 , and TiO_2 aerogels that can resistant to 1300 °C had been obtained.^[12,69,70] During the process of preparation of this review, fiber-reinforced Al_2O_3 - SiO_2 composite aerogels have been reported, and they exhibited impressive HTR up to

1500 °C with ultralow shrinkage. Apparently, hybrid structure design toward HTRAs is a strong and effective approach.

The mechanical properties of aerogels would be decreased under high temperatures. When the temperature rises, the amplitude of the internal atoms increases and result in the increases of atom distance, then the interaction between atoms force is reduced, which reduces the mechanical properties of the aerogel.

For ceramic aerogel, the thermal conductivity of polycrystalline structure is lower than that of single crystal structure, because in polycrystalline, the crystal grain size is small, there are many grain boundaries and defects.^[71,72] The thermal conduction phonons are easy to scatter so the thermal conductivity is lower. As temperature rises, the difference becomes more pronounced. In addition, at high temperatures, the aerogel may also undergo crystal transformation and

Fig. 3 Preparation methods of HTRAs: (a) sol-gel transition approach, (b) sacrificial template method, (c) solution spinning method (Reproduced with the permission from [99], Copyright 2020 The authors), (4) chemical vapor deposition method. (Reproduced with permission from [101], Copyright 2018 American Chemical Society)

growth, resulting in the decreases of SSAs.^[59]

3. Synthetic strategy of HTRAs

In this section, the synthetic strategies of HTRAs are introduced. The most applied methods including the traditional sol-gel transition approach, sacrificial template strategy, solution blown spinning method, and chemical vapor deposition.

3.1 Sol-gel transition approach

Since the first SiO₂ aerogels were synthesized by Kistler in 1931,^[20,73] sol-gel transition approach has become the most

widely used method to synthesize aerogels. It is a method of wet chemistry by construction a porous network from a bottom-up strategy in a liquid medium at low temperature (generally below at 100 °C).^[74] The Preparation of HTRAs involves two successive stages: Formation of a colloidal suspension from the precursors (sol) and subsequent formation of a three dimensional (3D) porous network (gel) (Fig. 3a). The microstructure of the aerogels is determined by the two stages, which is critical for the performance of the aerogels. For both stages, the driving reactions are hydrolysis and condensation, respectively. The freeze drying method has been booming in recent year, but it's not suitable for drying

gels formed by sol-gel transition because this method normally result in pore reforming or the broken of the network.^[75] Recently, ceramic aerogels obtained by sol-gel process, such as oxide (Al_2O_3 , ZrO_2) and nonoxide (Silicon carbide (SiC), Boron nitride (BN)), have been reported,^[25,27,76,77] which present a new perspective for the application of thermal insulation in high temperatures higher than 800 °C. These aerogels commonly exhibit ultra-low thermal conductivity and high porosity.^[78] For example, SiO_2 aerogel obtained by supercritical drying usually shows good thermal stability and low thermal conductivity as low as 0.010 W/m·K.^[73] In sum, the sol-gel approach is versatile and most of the HTRAs could be synthesized by this method. However, the microstructures of these aerogels are less controllable due to the sol-gel transition.

3.2 Sacrificial template method

Another commonly used manufacturing method to produce HTRAs is the replication of templates technique, in which a porous material is used as a template (a matrix) and aerogel precursors are filled in the pores in the form of suspension or slurry (sol). After gelation, the template is pyrolyzed and removed to obtain the aerogels (Fig. 3b).^[78] According to the differences in removing the templates, the sacrificial template method can be further divided into two methods: (1) "soft template method", in which the templates could be decomposed at low temperatures (such as polymers and wood)^[79-81] and a porous sample is left; and (2) "hard template method", in which the templates could not be decomposed during heat treatment but could be removed by other processes such as acid treatment.^[82,83]

The merits of the template method are that it can be used to produce porous ceramic aerogels with controllable pore structures (shapes, sizes, and numbers, determined by the original templates), chemical compositions (determined by the type of pre-ceramic precursor), and processing conditions. Generally, aerogels produced by this method possess low strength due to its single-layer structure (unless repeated coating) and the highly porous pillars caused by the removal of templates.^[84] The template method is a commonly used method for pore creation, but this method has some limitations, e.g. the size of templates were normally large, thus the SSAs of the resulting aerogels were low.

3.3 Solution spinning method

Solution spinning method is a two-step process, in which nano building blocks (e.g., nanofibers, nanospheres) are first produced by solution blown spinning technique (such as electrospinning),^[85-96] then the nano building blocks are used to construct a porous network in solvent, as illustrated in Fig. 3c. This method can be used to synthesize various HTRAs, and the merits of the method is that structure of building blocks can be precisely predetermined. It's also simpler than the sacrificial template method. Wu *et al.* have used this method to prepare a series of porous foams (they called as

aerogels) with HTR based on ZrO_2 and Al_2O_3 nanofibers.^[97,98] The ceramic aerogels obtained by this method exhibited high compressive resilience and fatigue resistance under strain up to 80%. The porous structure and high melting point of the ceramic aerogel make it have strong fire resistance up to 1000 °C and exhibited excellent heat insulation performance (0.034 W/mk).^[99] In addition, the anisotropic microstructure of the aerogels endowed them with sound absorption capacity ($\text{NRC}=0.77$). By changing different ceramic precursors, a variety of ceramic nanofiber sponges can be obtained, including TiO_2 , ZrO_2 , Yttrium stabilized zirconia, and BaTiO_3 .^[100] The simplicity and high efficiency of this method make it promising to be used in the fields of fire protection, high temperature insulation, sound wave absorption, etc. and it could be heated by methane flame at 1300 °C without any cracking.

3.4 Chemical vapor deposition

Chemical vapor deposition (CVD) can also be used to prepare HTRAs. The ceramic precursor obtains a 3D porous structure through thermal deposition or thermal decomposition, and then undergoes annealing treatment to obtain aerogels. Zhang *et al.* reported that siloxane xerogel had been used as a gas phase source to generate SiO and CO through high-temperature pyrolysis under argon conditions, then they self-assembled on a graphite cover substrate to form SiC nanofibrous aerogels (Fig. 3d).^[101] Interestingly, Si_3N_4 nanobelt aerogels with high compressibility and resilience, excellent fire resistance and HTR (1200 °C in ambient air) could also be prepared by this method by tuning the processing parameters.^[102] More importantly, the CVD method can be used to successfully scale up the production of SiC nanowires.^[103] Aerogel prepared by this method can be prepared with adjustable macrostructures (such as tube, block, and spherical building blocks) by changing the appearance and shape of the carbon source, which is important to obtain HTR performance.^[40]

4. Types of HTRAs

4.1 Oxide aerogel

The physical properties of aerogels are highly dependent on their chemical components. Silicon oxide, aluminum oxide, and boron nitride ceramic aerogels are excellent examples that can be resistant to extremely high temperatures due to the chemical components. Here, we will comprehensively introduce the HTRAs based on their compositions.

4.1.1 Silica (SiO_2) aerogel

In 1931, Kistler *et al.*^[20] used supercritical drying method to prepare porous SiO_2 aerogels for the first time. SiO_2 aerogels exhibit extremely low thermal conductivity (0.01 W/m·K),^[104] and the synthetic approach generally involves a sol-gel transition to form porous networks and a supercritical drying process to remove the liquid without shrinkage.^[17] Up to now, methyltrimethoxysilane (MTMS), Tetraethyl orthosilicate

(TEOS), tetramethoxysilane (TMOS), and water-glass (sodium silicate) are the most widely used precursors for the synthesis of SiO_2 aerogels, and the SiO_2 aerogels are the most successful aerogels that have been commercialized.^[19] However, native SiO_2 aerogels normally cannot be used at temperatures high than 600 °C. As the temperature rises, the Si-CH₃ and Si-OH groups are gradually degraded until disappeared. During the same time, the siloxane bridges increase. The primary particles are undergone expansion, while the pores are atrophy and collapsed. The density of SiO_2 aerogels is increased, and they are transformed from transparent to opaque and white. Finally, the structures are completely destroyed. It should be noted that the SiO_2 aerogels are mainly amorphous below 1200 °C.^[76]

Compared with traditional thermal insulation materials, SiO_2 aerogels have extremely low thermal conductivity and outstanding insulation performance, making themselves as ideal alternatives. However, due to the weak interaction between the nanoparticles (building blocks of SiO_2 aerogels are particles with diameters range from several nanometer to 30 nm and there is a neck-structure between the particles), SiO_2 aerogels exhibit inherent brittleness, poor mechanical strength, and flexibility.^[105-111] In order to realize the high-efficiency application of HTRAs under extreme conditions, the mechanical property of the aerogels should be paid specific attention. Fibrillating aerogel is one of the effective ways to improve the above defects, so as to avoid shrinkage during drying and reinforce the structures.^[5]

Fig. 4 Photo images of silica aerogels by using silica nanofibers as building blocks. (Reproduced with permission form [76], Copyright 2019 American Chemical Society)

By using flexible silica nanofibers as building blocks (precursors), Dou *et al.*^[27] successfully fabricated ceramic nanofibrous aerogels with HTR and excellent mechanical

properties, breaking through the current restrictions. This aerogel cannot only bear the burning of ultra-high temperature (about 1100 °C), but also could retain its initial shape even after heat treatment. In another similar experiment (Fig. 4). Dou *et al.*^[76] assembled a hierarchical cellular structured silica nanofibrous aerogel with the reconstruction of SiO_2 nanofibers. The aerogels could also withstand butane flame (1100 °C) burning while maintaining their resilience and elasticity for 10 minutes.

Silica nanotubes have also been used as building blocks, they are capable of overcoming the flaws of brittleness and improving the strength and heat-insulating property of metallic and ceramic aerogels.^[112] The development of nanotube aerogels provides new ideas for the structure and performance control. Based on the porous structure of the aerogels, the introduction of a continuous hollow core structure further improves the thermal insulation performance of the aerogels. For example, Du *et al.*^[67] obtained a new type of SiO_2 nanotube aerogel by imitating the pore structures of polar bear hairs. They used carbon aerogels as sacrificial skeletons, combined with chemical vapor deposition methods.^[38] This material has excellent thermal insulation properties and deserves further ultra-high temperature applications.

4.1.2 Alumina (Al_2O_3) aerogel

In addition to the above mentioned inorganic SiO_2 aerogels, the metal oxide alumina aerogels also possess good thermal effects and show a wide range of applications due to the unique structures of the materials. Compared with SiO_2 aerogels' sintering temperatures (above 600 °C), alumina aerogels have higher sintering temperatures (above 1000 °C), presenting one of the best heat resistance oxide aerogels.^[113]

Zu *et al.*^[70] drew support from innovative acetone-aniline *in situ* water formation (ISWF) method and two modification techniques to develop super heat-resistant and robust alumina aerogels. The highest heat resistant temperature of the alumina aerogels was up to 1300 °C. Several parameters may contribute to the enhancement of the stability of the aerogels, including density, molar ratio of modifiers, microstructures, degree of crystalline. The main reason for the capacity of temperature resistance of 1300 °C is the introduction of a core-shell structure (alumina core and a SiO_2 shell), which restricts the crystal growth of alumina nano building blocks during heat treatment, as has been discussed in section two.

Using polyvinylpyrrolidone (PVP) sponge as templates, combined with the controlled atom layer deposition (ALD) technology, Xu *et al.*^[97] prepared Al_2O_3 nanotube aerogels with low density, low thermal conductivity, excellent thermal stability, and high resilience properties at 900 °C for two hours. There was no limitation of templates by this method. The process of heating from 900 to 1200 °C was accompanied by crystallization and phase transition. Finally the Al_2O_3 nanotube aerogel's walls were completely broken.

4.1.3 Zirconia (ZrO_2) aerogel

Due to its ultrahigh temperature resistance up to 2200 °C, zirconia (ZrO_2) ceramics have aroused great research interest from both academy and industry.^[98] Precursors that can be used to synthesize zirconia aerogel including zirconium *n*-propoxide, *n*-propanol, and acetylacetone.^[114] The network of zirconia aerogels is similar to that of SiO_2 aerogels, which is a highly cross-linked network made up of zirconium oxide nanoparticles.^[114] This type of aerogels has been successfully applied in toughening ceramics, detectors, and photoelectron materials.^[105] For instance, Sun *et al.*^[115] invented a promising sol-gel transition and supercritical fluid drying approach to produce a thermally stable ultrafine tetragonal zirconia aerogel, which possessed high surface areas and large pore volumes. It is noteworthy that the heating treatment scarcely brings about the transition from the tetragonal to monoclinic phase, while the phase change will have a negative effect on the particle size and SSA.

The performance of zirconia aerogels can be remarkably increased by doping hybrid atoms (variable atoms and doping degree) or introducing nanofibrous building blocks.^[116] Because of the existence of oxygen vacancies in defect structures, ytterbia-doped zirconia aerogels prepared by Hurwitz *et al.*^[116] had a low thermal conductivity (2 W/mK) at extremely high temperature (1000 to 1200 °C). Doping process enabled better phase stability and lower thermal diffusivity. The porosity was in inverse relation to the thermal conductivity, and small pores disappeared quickly during thermal annealing.

Yttria-stabilized zirconia (YSZ) nanofiber sponges are available for high-temperature filter materials. Wang *et al.*^[100]

synthesized a YSZ nanofiber sponge showed excellent mechanical resilience at 800 °C and even 1300 °C. There were no shrinkage and cracking during the heating process, and it exhibited outstanding ability to recover after several compression cycles. This excellent thermal insulation material benefits from the highly porous structure and the low thermal conductivity of ZrO_2 .^[98,100]

4.2 Nitrides aerogels

Nitrides, with excellent thermal stability, chemical inertness, and low thermal expansion coefficient,^[117,118] have been used to synthesize aerogels with superior thermal and mechanical stability at high temperature.^[119–121] Especially, the nitrides aerogels show promising potential applications in high-temperature thermal insulation and catalyst supports.^[122] In this paper, the nitride aerogels, such as boron nitride and Si_3N_4 aerogels, which can be used in the high temperature environment above 800 °C, will be introduced.

4.2.1 Boron nitride (BN) aerogels

Ceramic aerogels with the combination of recoverable compressibility and outstanding high temperature heat resistance have drawn great interests. However, the ceramic aerogels suffered from serious strength degradation and structural collapse under high temperatures, which is rather brittle and shows crystallization-induced pulverization behavior.^[123] Boron nitride, an excellent functional material with high thermal conductivity, mechanical stability, and low coefficient of expansion, is a potential direction to solve the problems.^[124]

Fig. 5 Structure design and fabrication of the ceramic aerogel metamaterial. (a) Illustration of the metastructure design of ceramic aerogels. The units of the colored scale bars are as follows: kilopascals for NPR and percentage (with strain zoomed by 30 times) for NTEC. (b) Illustration of the CVD synthesis process of the double-paned hyperbolic ceramic aerogels. The NCFD technique is used to render hyperbolic structure in graphene aerogel templates by manipulating the ice crystal growth direction. (Reproduced with permission from [129], Copyright 2019 The authors and AAAS)

Recent studies indicated that the excellent thermal stability of boron nitride was mainly derived from its crystal structure.^[125-127] The aerogels made by hexagonal boron nitride (h-BN) showed excellent properties. For instance, Pham *et al.*^[128] reported the BN aerogels with highly crystalline turbostratic structures and excellent thermal stability up to 1000 °C. The BN aerogel can be used for oil absorption and can still retain over 93% of their original oil uptake capacity after regeneration. The superior thermal and mechanical stability of BN aerogels due to the intra layer bonding structure of the sp^2 -bonded hexagonal boron nitride (h-BN) (which is highly crystalline). TEM images indicated that the BN aerogels had a nanoporous structure with the sp^2 -bonded layers lying parallel to the pores, which proved the excellent thermal and mechanical stability.

Xu *et al.*^[129] designed and synthesized a hexagonal boron nitride (h-BN) aerogel with 2D nanosheets by using a modified hydro-thermal reduction (MHR) and non-contact freeze drying (NCFD) technique, as shown in Fig. 5. The BN aerogel had a hierarchical porous structure with hyperbolic architecture, which exhibited ultralow density, thermal superinsulation, and long-term high-temperature exposures at 900 °C in air. The 2D nanosheets were face-to-face stacked and formed nearly isolated cells, which can effectively reduce the air conduction and convection, producing ultralow thermal conductivities below stationary air.^[130]

In addition to native aerogels, boron nitride can also be combined with other aerogels in different forms like powder and nanotubes in order to improve its heat resistance and mechanical properties. Xia *et al.*^[131] synthesized carbon nanotube (rCNT) aerogels by embedding carbon-doped boron nitride (BN) structures to improve its desulfurisation

performance. The results demonstrated that hybridizing BN with 3D nanocarbon networks was an effective way to enhance the properties of BN aerogels. The conductivity of the CNT scaffold enabled resistive heating of BN to high temperatures up to 700 °C at low energy inputs. Yang *et al.*^[132] prepared the BN/SiOC aerogel composites prepared by a sol-gel and pyrolysis method, the aerogel exhibited high compressive strength and high heat resistance at 1300 °C due to the presence of BN particles. The results showed that addition of BN particles can increase the density of the aerogel, which makes it denser and contributes to the improvement of its strength.

4.2.2 Silicon Nitride (Si_3N_4) aerogels

SiO_2 aerogel is the most widely used aerogel with relative high thermal stability, but it is difficult to use SiO_2 aerogels individually at higher temperature over 600 °C.^[133] To improve the thermal stability, SiO_2 aerogel powders have been used as precursors to prepare SiC and Si_3N_4 aerogels by carbothermal reduction in the flow of Ar or N_2 . The thermal conductivities of the aerogels were 0.163 and 0.070 W/m K, respectively.^[134] The method by carbothermal reduction in flowing N_2 is widely used to prepare Si_3N_4 aerogels. Kong *et al.*^[135] had used one-step sol-gel process and supercritical fluid drying to synthesize C/ SiO_2 (RF/ SiO_2) aerogels. To improve the thermal stability, monolithic silicon nitride (Si_3N_4) aerogel (SNA) was prepared via carbothermal nitridation of the RF/ SiO_2 aerogels (RFSA) in flowing N_2 . Fig. 6 showed the schematic description of the formation of the RFSA and its evolution into the SNA. The TGA of the SNA showed no substantial weight loss below 600 - 800 °C, and Si_3N_4 nanocrystals were formed from RFSA at a carbothermal temperature of 1500 °C.

Fig. 6 Schematic of the formation of the RFSA and its evolution into the SNA. (Reproduced with the permission from [135], Copyright 2019 Elsevier Ltd.)

By using a home-made free-standing α -Si₃N₄ crystalized paper as precursor, ultralight α -Si₃N₄ NB aerogels (NBAs) with tunable densities have been prepared via a facile partial-hot-pressing treatment process. The strategy was cheap and convenient, and the density of the resulted aerogels could be well-controlled. The ultralight α -Si₃N₄ NBAs has unique properties such as resilient compressibility, mechanical energy dissipation, and excellent fire resistance at 1200 °C, which makes it a promising candidate for mechanical energy dissipative, fire-resistant, and electronic wave-transparent thermal insulator applications in extreme conditions.

4.2.3 Other Nitride aerogels

Silicoboron carbonitride (SiBCN) aerogels are types of HTRAs with low density, superior oxidation resistance, and creep resistance.^[136] Song *et al.*^[137] used polymer derived ceramic (PDC) as building blocks to fabricate RGO-SiCnw/SiBCN composite ceramics by a chemical vapor infiltration (CVI) technology. The results indicated that the RGO-SiCnw/SiBCN composite ceramic aerogels maintained outstanding electromagnetic wave (EMW) absorption ability with minimum RC of -10.41 dB after oxidation at 900 °C, suggesting that the RGO-SiCnw/SiBCN composite ceramic aerogels are excellent EMW absorption materials that can be used at extremely high temperatures and harsh environments.

Besides, various aerogels such as carbon nitride (C₃N₄) and titanium nitride (TN) aerogels have also been synthesized, which would possess high temperature resistant properties. However, these aerogels are mostly used for efficient photocatalyst with optimal structure, the temperature resistance properties were not reported.^[138,139]

4.3 Carbide aerogels

The first type of carbide aerogel was silicon carbide (SiC) aerogel, which was prepared by Leventis *et al.* in 2010 via a click chemistry.^[140] Since then, carbide aerogels have received increasing attentions. Carbide is high temperature resistant, wear resistant, corrosion resistant, and it possesses high melting point, high hardness, good electrical conductivity, and robust mechanical properties. Although carbide itself has high thermal conductivity, it can be used as an excellent heat insulation material after been converted to highly porous aerogels. Up to now, the most popular carbide aerogels are SiC aerogels, which are normally synthesized by mixing SiO₂ aerogel and carbon source followed by carbon thermal reduction reaction as illustrated in the equation presented as below:^[141,142]

Inspired by this approach, Chen *et al.*^[143] adopted a low-temperature pseudomorphic synthesis approach to form Nb-iodine and Ti-iodine compounds. Then, the complex diffuses onto the skeleton surface of the carbon aerogel and reacts with the carbon uniformly to form the TiC and NbC aerogel.

SiC aerogels have excellent high-temperature chemical stability and heat resistance, superior to oxide ceramics and nitride aerogels, which are expected to be used in various applications under extreme conditions, especially in ultra-high temperature environments above 1300 °C. The preparation of carbide ceramic aerogels is usually complicated due to the oxidation reaction of carbon in the presence of oxygen, which limited the development of carbide ceramic aerogels, and the main ceramic aerogels reported so far are SiC and TiC. The oxide temperatures of some carbide ceramics are listed in Table 1.^[146-153] Silicon carbide is widely used in aerospace and other fields due to its high hardness, high strength, high thermal conductivity, low electrical conductivity, and high oxidation resistance (more than 1100 °C in ambient air).^[84,144,145]

Table 1. The oxidation resistance temperature of some carbides

Types of carbide ceramics	Oxidation temperature (°C)
TiC	1100-1400
ZrC	
TaC	
NbC	
VC	800-1100
WC	
SiC	1300-1400

As has been mentioned above, it is difficult to obtain silicon carbide aerogels by the sol-gel transition due to the limited monomers. However, Wang *et al.*^[101] successfully prepared silicon carbide aerogels with intertwined nanowires and highly porous structures through the nucleation of SiC nanowires by chemical deposition reactions on a graphite cap. The growth direction of SiC nanowires was random (Fig. 7a). The flexibility and durability of the method for the preparation of elastic ceramic aerogels can be adjusted by the process parameters. Chen *et al.*^[154] proposed the conversion of RF/SiO₂ aerogel to SiC aerogel using template-limited magnesium thermal reaction method at low temperature of 700 °C in 2012. The apparent density of the product was about 130 mg/cm³, the SSA was about 230 m²/g, and the porosity was about 90%. Compared with the results of Leventis (Fig. 7b),^[140] the aerogel synthesized by this process has a smaller apparent density and larger SSA.

Zhou *et al.*^[81] reported a new method to prepare porous SiC/C ceramics in 2015. In this method, liquid polycarbon silane (LPCS) were impregnated into charred pine wood under vacuum to create a low density (~0.72 g/cm³) and high open porosity (~70 vol%) composite aerogel, then it was ceramicization at 1500 °C to obtain a SiC/C ceramics aerogel. They have almost the same structure of the wood (Fig. 7c), and exhibited a high compressive strength of about 37.23 MPa. By oriented freezing of a suspension of SiC fibers, SiC aerogels with porosity over 90% and density below 300 mg/cm³ were prepared (Fig. 7d).^[155] The directional freezing method gave birth to lattices pores with layered architectures,

Fig. 7 (a) High temperature resistant SiC nanowire aerogel. (Reproduced with the permission from [101], Copyright 2018 American Chemical Society) (b) Nitrogen sorption isotherms of F-20-45 samples. (Reproduced with the permission from [140], Copyright 2010 American Chemical Society) (c) SEM micrograph (BSE image) of porous SiC/C ceramized at 1500 °C. (Reproduced with the permission from [81], Copyright 2015 Elsevier Ltd.) (d) Schematic of the freeze casting process and SEM of SiC aerogel. (Reproduced with permission from [155], Copyright 2016 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim) (e) Fabrication of highly porous SiC and Si₃N₄ shaped objects. (Reproduced with the permission from [134], Copyright 2018 American Chemical Society) (f) Illustration of the different responses of the shell and core of the SiC sponges during the compression test. (Reproduced with the permission from [156], Copyright 2019 American Chemical Society)

result in SiC aerogels with low density while maintained mechanical strength and stability at high temperatures. The pores and pillar dimensions and mechanical properties of the SiC aerogels were comparable to those of microlattices prepared by thin-layer deposition, resulting structures with high strength (up to 3 MPa) and stiffness (up to 0.3 GPa). In 2018, Leventis *et al.*^[134] obtained SiC aerogels by using a multiscale nanoparticles as building blocks (Fig. 7e). This approach utilized the topology generated by the carbon thermal reaction, while the porosity relies on the gas space created by the carbon reaction drop. This makes it feasible to fabricate aerogels from xerogels. In fact, the use of polyester

cross-linked xerogel powder compacts as ceramic precursors, rather than monomeric polymers. Thus, the method is relative simple, efficient, energy and material economic, and versatile. Zhu *et al.*^[156] used in-situ template and NH₄Cl foaming method to prepare SiC foam (Fig. 7f), which was successfully used in the field of pressure sensors by virtue of its high elastic conductivity. In addition, SiC is expected to be applied in the direction of high temperature sensing due to its HTR. There are few reports on other carbides aerogels. But titanium carbide composite aerogels have recently been reported by Du *et al.*^[157] The nanoporous TiC/C composite aerogels with apparent density of 339.5 mg/cm³ and specific surface area of

Table 2. Composition, microstructure, and physical properties of some HTRAs.

Materials	Microstructure	Density (mg·cm ⁻³)	Temperature resistance (°C)	Thermal conductivity (W/(m·K))	Ref
SiO ₂	Hierarchical Cellular	0.2	1100	0.02327	[76]
SiO ₂	Nanofibrous Interweaved				
SiO ₂	Cellular	0.2–17	1100	0.0223	[27]
Al ₂ O ₃ , ZrO ₂	Nanofibrous Hierarchical				
Al ₂ O ₃ , ZrO ₂	Cellular		1300	0.0322 at 1300 °C	[77]
Al ₂ O ₃ , SiO ₂	Nanofibrous nanofibers	34.64–48.89	1200	0.03274 – 0.04317	[160]
Alumina–silica aerogel	Micron fibers and nanoparticles	0.36	1500	0.082 at 1200 °C	[68]
Al ₂ O ₃	Randomly interconnected networks		1300	0.031	[70]
Al ₂ O ₃	Nanotubes	0.68	900	0.022	[97]
Yttria-Stabilized ZrO ₂	Random nanofibers	20	1300		[98]
ZrO ₂	Reticulate structure	0.13	1100		[166]
BN	Nanolayered double-pane walls	5	900	0.02	[129]
BN	Nanobelts	15.5	1000	0.0346 ± 0.0015	[167]
BN	Nanosheets	60	1000		[128]
Si ₃ N ₄	Nanobelts	1.8 - 9.6	1200	0.029	[102]
SiC	Nanowires	5		0.026	[101]
SiC	Nanowires	11	1000	0.025	[103]
SiC	Nanofibers	23	1100		[40]
HfB ₂	Nanoparticles	413-881		0.18 to 0.33	[168]
ZrB ₂	Nanoparticles	407-1058			[168]

459.5 m²/g were prepared through acid catalysis. The preparation reaction temperature of the aerogels was lower than 800 °C, and the aerogels had good photothermal conversion ability. This method is expected to solve the bottleneck problem of preparing nanoscale titanium carbide materials with controllable structure.

4.4 Other aerogels

In addition to single-component aerogels, various composite aerogels that combined with different oxide components and structures have also been extensively studied, which endows aerogels with excellent thermal properties.^[88] Oxide composite aerogels is aimed at improving the comprehensive performance of the target aerogels, which can realize the structure and performance regulation. For instance, various oxide composite aerogels with both superior mechanical and thermal properties have been reported, such as silica-based^[158] and alumina-based composite aerogels.^[77,159-161]

The temperature resistance of some single component aerogel and composite aerogels are summarized in Table 2. As some doped ions stabilize grains, oxide composite aerogels such as yttrium oxide stabilized zirconia (YSZ) and yttrium aluminum garnet (YAG) have higher high temperature stability (1300 °C or higher), which stimulated scientists to explore composite aerogels with higher temperature resistance. As shown in Fig. 8a, Liu *et al.* prepared YSZ aerogels by a simple non-toxic gel method (citric acid).^[162] The gelation time of the wet gel and the density of the corresponding aerogel could be adjusted by the content of gel agent, and the SSA of YSZ aerogel could be adjusted from 214 to 490 m²/g. When calcined at high temperatures (1000 °C), the SSA of the aerogel can be well preserved, making it suitable for the application in ultra-high temperature catalysis. Through the microstructure design, Zhi *et al.* (Fig. 8b) obtained Y-Zr-Al aerogel with low thermal conductivity (0.032 W/mK) and high elastic modulus (3.47 MPa).^[163] The aerogel was synthesized

Fig. 8 (a). Nitrogen adsorption–desorption isotherms for the samples of YSZ aerogel and the pore size distributions. (Reproduced with the permission from [162], Copyright RSC Publishing). (b) Apparent photos of different micro-nano YSZ-Al₂O₃ composite aerogels. ((Reproduced with the permission from [163], Copyright 2017 Elsevier). (c) Schematic illustrating the preparation of ASZ and Optical image showing the high-temperature resistance of the ASZ paper. (Reproduced with the permission from [164], Copyright 2020 American Chemical Society). (d) SEM images of quartz fiber/Al₂O₃-SiO₂ aerogel composite. (Reproduced with the permission from [165], Copyright 2020 American Chemical Society)

by sol-gel technology, and the network was built up with hollow microspheres. They can withstand extremely high temperature of 1200 °C in aerobic environment. Using spinnable precursors, Wu *et al.*^[164] obtained Al₂O₃-stabilized ZrO₂ (ASZ) air filter paper through the spray spinning method (Fig. 8c). Zirconia was found to be stabilized by alumina, and the grain size was reduced, which improved the HTR and stability of the air filter paper. Moreover, they also synthesized YSZ nanofiber sponge showed excellent mechanical resilience at 800 °C and even 1300 °C. There were no shrinkage and cracking during the heating process, and it exhibited outstanding ability to recover after several compression cycles. This excellent thermal insulation material benefits from the highly porous structure and the low thermal conductivity of ZrO₂.^[98,100] It is noteworthy that the mullite phase has a high thermal stability. By adding silicon oxide to alumina, the mullite phase ceramic aerogels have high thermal stability and low thermal conductivity, as well as high SSA. In addition, the composite phase can not only improve the mechanical stability of the material, but also restrain the damage of the internal structure of the material. Wang *et al.*^[165] obtained a fiber-reinforced mullite aerogel with quartz fiber

Fig. 9 Unique position of UHTC aerogels in an Ashby-type diagram of the melting temperature vs thermal conductivity form multiple classes of high-temperature materials. (Reproduced with the permission from [168], Copyright 2019 American Chemical Society)

reinforced matrix by controlling Si-Al (3:1). The microstructure of the fiber-reinforced mullite aerogel is stable and unchanged at 1100 °C (Fig. 8d).

Aerogels prepared by transition metal oxides (e.g. ZrO₂, TiO₂, and HfO₂) have also been reported,^[169-175] but they have a lower melting point than borides, though this type of aerogels is relative few. By means of epoxy propane cross-linked gel and boron thermal reduction, Worsley *et al.* obtained zirconium boride and hafnium boride aerogels with ultra-high temperature resistance respectively by using different precursor materials (UHTC in Fig. 9).^[168,169] Although the SSA of the aerogels was small, it opened the way for the development of boride aerogels. In conclusion, the combination is another effective way to significantly improve the upper limit of temperature resistance of aerogels.

4.5 Applications of HTRAs

High-temperature processes are widely used in various emerging industries^[176-179] and aerospace.^[180] The thermal properties of materials at high temperatures play an important role. Various materials are being produced and used at high temperatures above 800 °C. For example, when the space shuttle returns to the atmosphere, due to the high Mach number (> 5) of the flight, aerodynamic heating occurs, accompanied by a rapid increase in the surface temperature of the aircraft.^[181] The temperature of some parts will exceed

1000 °C for a long time. In order to ensure the safety of its internal equipment, high-efficiency insulation materials with low thermal conductivity must be used in these cases. Meanwhile, in order to reduce the transportation cost of the space shuttle, the thickness or density of the insulation layer should be as low as possible so as to achieve substantial weight reduction. Apparently, aerogels with efficient thermal insulation (low thermal conductivity ~0.010 W/mK) and extremely low density (~0.016 mg/cm³) are ideal candidates in the aerospace field.^[182-184]

Besides, many industrial fields face extremely high operating temperatures during the production process. For example, the internal operating temperature of the conversion equipment and connecting pipelines in the hydrogen production plant is usually above 700 °C, and the tank calciner is heat-treated in the absence of air. The temperature of the channel and the temperature of combustion can be as high as 1300 ~ 1500 °C. Solid oxide fuel cell (SOFC) is an important energy conversion development technology that can achieve higher efficiency than internal combustion engines.^[185] Despite great efforts to lower the operating temperature, due to the requirements for catalytic oxygen reduction kinetics, the best SOFCs still operate at high operating temperatures (~850 °C).^[186] Therefore, in order to maintain the safe and stable operation of the device, it is very important to establish an efficient thermal protection system for insulation.

Fig. 10 Photographs on oil absorption properties of a BN aerogel. (a-c) Absorption and burning process of cyclohexane (stained with Sudan Red II and floating on water) by the BN aerogel within 5 s. (d-f) BN aerogel after burning in air reused for absorption of cyclohexane. (Reproduced with the permission from [190], Copyright 2015 Nature Publishing Group)

In the aforementioned applications, HTRAs would be ideal candidates. Although a number of HTRAs have been reported so far, and the original intention for the synthesis of HTRAs is indeed to be applied in high temperatures, examples of them been used for this purpose is few. Nevertheless, the HTRAs could be used in various fields as the traditional aerogels can do. Here we summarized some applications of the HTRAs. Firstly, they have been reported as adsorption and purification materials.^[187,188] For example, a nitrogen-doped carbon aerogel has a very high carbon dioxide absorption capacity (~16 wt%).^[189] As shown in Fig. 10, the BN aerogel prepared by using borane as a source of boron and nitrogen can absorb 160 times its own weight in a short period of time. Due to its high temperature oxidation resistance, the BN aerogel after oil absorption can be restored to use simply by burning in air. It can be recycled as a water treatment tool.^[190]

About 90% of industrial processes use catalysts, and sometimes a suitable catalyst carrier can greatly increase the activity of the catalyst.^[191] The second example of application of the HTRAs is in catalysis. The new CeO₂-SiO₂ aerogel nanocomposite material obtained by controlling the growth of CeO₂ nanoparticles in the SiO₂ aerogel matrix can show very good thermal stability at temperatures up to 900 °C. It can be applied to the field of heterogeneous gas phase catalysis, the heterogeneous catalyst of water gas shift reaction ($\text{CO} + \text{H}_2\text{O} = \text{CO}_2 + \text{H}_2$ catalyst is CeO₂).^[192,193]

Third, HTRAs can be used as filter for automobile exhaust gas, in which HTR is required. Air pollution has become a global environmental problem, mainly including particulate

matter emitted from automobiles, industrial production, and the burning of fossil fuels. Such substances have already caused a great threat to the ecosystem and public health. Most of the pollution caused by particles emitted by human activities is usually at a high temperature. Wang *et al.*^[98] reported a based on yttria-stabilized ZrO₂ (YSZ) nanofiber sponge filter produced with solution blown spinning process, which has the characteristics of elasticity, heat resistance and high efficiency. As shown in the high temperature filtration test shown in Fig. 11, it can be seen that at a high temperature of 750 °C and a high air velocity of 10 cm·s⁻¹, the filtration efficiency of the ceramic sponge for particles with a size of 0.3–2.5 microns can still be maintained at 99.97 %.

Fourth, THRAs used as high temperature sensors. The porous ceramic sponge composed of entangled ceramic nanofibers can be used as a piezoresistive sensor because of its sufficient mechanical strength, resistance to brittleness and a certain degree of compression recovery. Among them, silicon carbide (SiC) with nanostructures, which has a large SSA, thermal stability, and strong chemical inertness, is considered to be a promising candidate for microelectromechanical system (MEMS) sensing components.^[194] Xia *et al.* reported a SiC nanowire (SiCNW) sponge with low density (115 - 125 mg/cm³), good mechanical properties (compressive modulus of about 1.35 MPa) and electromechanical induction (gauge factor up to 87).^[156] In addition, the thermal conductivity of SiCNW sponge at room temperature is low, about 1.01 W/mK, indicating that it has a certain potential to monitor structural damage or capture impact in high-temperature environments.

Fig. 11 Filtration test at high temperature. (a) Schematic of high-temperature PM filtration measurement setup. (b) Concentration of PM particle before and after filtrating at 750 °C. (c) PM measurement of automobile exhaust gas with YSZ nanofiber sponge filter. (d) Filtration efficiency for different particle sizes of automobile exhaust gas. (a-d Reproduced with the permission from [98], copyright 2018 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim)

5. Conclusions

In sum, recent progress in HTRAs have been comprehensively reviewed, these including the types of aerogels that can be used in high temperatures, synthetic methods for the HTRAs, the mechanism how to obtain HTR properties, and finally the applications of the HTRAs are discussed and summarized. Up to now, HTRA that can be resistant to 1500 °C has been obtained, which is composite aerogel composed by SiO₂ and Al₂O₃. Specifically, Table 2 summarize the composite, microstructure, and some physical properties of the HTRAs, which gives a brief and clear overview on the types of HTRAs. Nevertheless, the application of the HTRAs for light weighted thermal insulation in extremely high temperatures is yet to be reported, and the practical effect of the HTRAs in high temperature thermal insulation should be carefully verify by various experiments.

In the near future, HTRAs with higher resistant temperature more than 1500 °C would be soon produced. But it's still a challenge because to achieve this target, both the chemical composition and microstructure of the aerogels should be well designed. First, building blocks of the targets aerogels should possess high thermal stability, they cannot be degraded. Second, phase transition and crystal growth of the building blocks must be suppressed. Thus, the elements or compound such as SiC, Tungsten, YSZ, HfO₂, and Ta₄HfC₅ would be ideal building blocks for HTRAs that may resistant to extremely high temperatures. Challenges remain in the precursors and sol-gel transition of these compounds. Another promising direction for the HTRAs would be the introduction of a sacrificial layer, in which the surface of the monolithic aerogels were ceramic with compact, none porous structure, Then the inner part of the monolithic aerogels were protected by the outer ceramic layer and kept unchanged due the porous aerogel structure, in which temperature may be significantly reduced. Besides, mechanical strength and robustness of the HTRAs are also important, which may determine whether they could be practically applied.

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Conflict of Interest

There is no conflict of interest.

Supporting Information

Not applicable.

References

- [1] Z. Liu, Y. Ran, J. Xi, J. Wang, *Soft Matter*, 2020, **16**, 9160-9175, doi: 10.1039/d0sm01261k.
- [2] S. Kim, K. Kim, G. Jun, W. Hwang, *ACS Nano*, 2020, **14**, 17233-17240, doi: 10.1021/acsnano.0c07206.
- [3] S. Zhao, H. B. Zhang, J. Q. Luo, Q. W. Wang, B. Xu, S. Hong, Z. Z. Yu, *ACS Nano*, 2018, **12**, 11193-11202, doi: 10.1021/acsnano.8b05739.
- [4] L. Zhang, Y. Liao, Y. C. Wang, S. Zhang, W. Yang, X. Pan, Z. L. Wang, *Advanced Functional Materials*, 2020, **30**, 2001763, doi: 10.1002/adfm.202001763.
- [5] T. Linhares, M. T. Pessoa de Amorim, L. Durães, *Journal of Materials Chemistry A*, 2019, **7**, 22768-22802, doi: 10.1039/c9ta04811a.
- [6] J. Yang, Y. Li, Y. Zheng, Y. Xu, Z. Zheng, X. Chen, W. Liu, *Small*, 2019, **15**, 1902826, doi: 10.1002/smll.201902826.
- [7] C. Buratti, E. Belloni, F. Merli, M. Zinzi, *Energy and Buildings*, 2021, **231**, 110587, doi: 10.1016/j.enbuild.2020.110587.
- [8] S. Qie, Y. Hao, Z. Liu, J. Wang, J. Xi, *Acta Chimica Sinica*, 2020, **78**, 232, doi: 10.6023/a20010006.
- [9] J. Wang, J. Wang, *Acta Chimica Sinica*, 2021, **79**, 430, doi: 10.6023/a20110531.
- [10] J. Feng, B. L. Su, H. Xia, S. Zhao, C. Gao, L. Wang, O. Ogbeide, J. Feng, T. Hasan, *Chemical Society Reviews*, 2021, **50**, 3842-3888, doi: 10.1039/c9cs00757a.
- [11] E. Cuce, P. M. Cuce, C. J. Wood, S. B. Riffat, *Renewable and Sustainable Energy Reviews*, 2014, **34**, 273-299, doi: 10.1016/j.rser.2014.03.017.
- [12] X. Xu, S. Fu, J. Guo, H. Li, Y. Huang, X. Duan, *Materials Today*, 2021, **42**, 162-177, doi: 10.1016/j.mattod.2020.09.034.
- [13] L. Su, M. Niu, D. Lu, Z. Cai, M. Li, H. Wang, *Journal of Materials Science & Technology*, 2021, **75**, 1-13, doi: 10.1016/j.jmst.2020.10.018.
- [14] F. Peng, Y. Jiang, J. Feng, L. Li, H. Cai, J. Feng, *Journal of the European Ceramic Society*, 2020, **40**, 2480-2488, doi: 10.1016/j.jeurceramsoc.2020.01.058.
- [15] H. Cai, Y. Jiang, J. Feng, S. Zhang, F. Peng, Y. Xiao, L. Li, J. Feng, *Materials & Design*, 2020, **191**, 108640, doi: 10.1016/j.matdes.2020.108640.
- [16] M. A. Aegerter, N. Leventis, M. M. Koebel, *Aerogels Handbook*, *Springer Science & Business Media*, 2011.
- [17] N. Hüsing, U. Schubert, *Angewandte Chemie International Edition*, 1998, **37**, 22-45, doi: 10.1002/(sici)1521-3773(19980202)37:1/22:aid-anie22>3.0.co;2-i.
- [18] A. Du, B. Zhou, Z. Zhang, J. Shen, *Materials*, 2013, **6**, 941-968, doi: 10.3390/ma6030941.
- [19] N. Ganonyan, N. Benmelech, G. Bar, R. Gvishi, D. Avnir, *Materials Today*, 2020, **33**, 24-35, doi: 10.1016/j.mattod.2019.09.021.
- [20] S. S. Kistler, *Nature*, 1931, **127**, 741, doi: 10.1038/127741a0.
- [21] G. Nicolaon, S. Teichner, *Bulletin de la Société Chimique de Paris*, 1968, **5**, 1900-1906.
- [22] R. E. Russo, A. J. Hunt, *Journal of Non-Crystalline Solids*, 1986, **86**, 219-230, doi: 10.1016/0022-3093(86)90490-4.
- [23] A. F. Bedilo, K. J. Klabunde, *Nanostructured Materials*, 1997, **8**, 119-135, doi: 10.1016/s0965-9773(97)00011-1.
- [24] K. K. Kalebaila, D. G. Georgiev, S. L. Brock, *Journal of Non-Crystalline Solids*, 2006, **352**, 232-240, doi: 10.1016/j.jnoncrysol.2005.11.035.
- [25] B. Wang, G. Li, L. Xu, J. Liao, X. Zhang, *ACS Nano*, 2020, **14**, 16590-16599, doi: 10.1021/acsnano.0c05931.

- [26] Y. Du, X. Zhang, J. Wang, Z. Liu, K. Zhang, X. Ji, Y. You, X. Zhang, *ACS Nano*, 2020, **14**, 11919-11928, doi: 10.1021/acsnano.0c05016.
- [27] L. Dou, X. Zhang, H. Shan, X. Cheng, Y. Si, J. Yu, B. Ding, *Advanced Functional Materials*, 2020, **30**, 2005928, doi: 10.1002/adfm.202005928.
- [28] G. Li, G. Hong, D. Dong, W. Song, X. Zhang, *Advanced Materials*, 2018, **30**, 1801754, doi: 10.1002/adma.201801754.
- [29] M. Yang, N. Zhao, Y. Cui, W. Gao, Q. Zhao, C. Gao, H. Bai, T. Xie, *ACS Nano*, 2017, **11**, 6817-6824, doi: 10.1021/acsnano.7b01815.
- [30] J. Cai, J. Tian, H. Gu, Z. Guo, *ES Materials & Manufacturing*, 2019, **6**, 68-74, doi: 10.30919/esmm5f611.
- [31] Z. Chen, Y. Hu, H. Zhuo, L. Liu, S. Jing, L. Zhong, X. Peng, R. C. Sun, *Chemistry of Materials*, 2019, **31**, 3301-3312, doi: 10.1021/acs.chemmater.9b00259.
- [32] J. Liu, H. B. Zhang, X. Xie, R. Yang, Z. Liu, Y. Liu, Z. Z. Yu, *Small*, 2018, **14**, 1802479, doi: 10.1002/smll.201802479.
- [33] Z. Liu, L. Liu, Z. Zhong, Y. Ran, J. Xi, J. Wang, *RSC Advances*, 2021, **11**, 7331-7337, doi: 10.1039/d1ra00418b.
- [34] J. Wang, Q. Fang, L. Ye, A. Zhang, Z. G. Feng, *Soft Matter*, 2020, **16**, 5906-5909, doi: 10.1039/d0sm00979b.
- [35] J. Wang, R. Du, X. Zhang, *ACS Applied Materials & Interfaces*, 2018, **10**, 1468-1473, doi: 10.1021/acsami.7b18741.
- [36] J. Wang, X. Wang, X. Zhang, *Journal of Materials Chemistry A*, 2017, **5**, 4308-4313, doi: 10.1039/c6ta09677h.
- [37] D. Huang, C. Guo, M. Zhang, L. Shi, *Materials & Design*, 2017, **129**, 82-90, doi: 10.1016/j.matdes.2017.05.024.
- [38] H. J. Zhan, K. J. Wu, Y. L. Hu, J. W. Liu, H. Li, X. Guo, J. Xu, Y. Yang, Z. L. Yu, H. L. Gao, X. S. Luo, J. F. Chen, Y. Ni, S. H. Yu, *Chem*, 2019, **5**, 1871-1882, doi: 10.1016/j.chempr.2019.04.025.
- [39] Z. An, R. Zhang, D. Fang, *Ceramics International*, 2019, **45**, 11368-11374, doi: 10.1016/j.ceramint.2019.02.216.
- [40] B. Ren, J. Liu, Y. Rong, L. Wang, Y. Lu, X. Xi, J. Yang, *ACS Nano*, 2019, **13**, 11603-11612, doi: 10.1021/acsnano.9b05406.
- [41] J. Renteria, D. Nika, A. Balandin, *Applied Sciences*, 2014, **4**, 525-547, doi: 10.3390/app4040525.
- [42] A. A. Balandin, *Nature Materials*, 2011, **10**, 569-581, doi: 10.1038/nmat3064.
- [43] S. Takeshita, S. Yoda, *Industrial & Engineering Chemistry Research*, 2018, **57**, 10421-10430, doi: 10.1021/acs.iecr.8b02332.
- [44] P. Hu, J. Lyu, C. Fu, W. B. Gong, J. Liao, W. Lu, Y. Chen, X. Zhang, *ACS Nano*, 2020, **14**, 688-697, doi: 10.1021/acsnano.9b07459.
- [45] W. Sakuma, S. Yamasaki, S. Fujisawa, T. Kodama, J. Shiomi, K. Kanamori, T. Saito, *ACS Nano*, 2021, **15**, 1436-1444, doi: 10.1021/acsnano.0c08769.
- [46] J. Song, C. Chen, Z. Yang, Y. Kuang, T. Li, Y. Li, H. Huang, I. Kierzewski, B. Liu, S. He, T. Gao, S. U. Yurker, A. Gong, B. Yang, L. Hu, *ACS Nano*, 2018, **12**, 140-147, doi: 10.1021/acsnano.7b04246.
- [47] X. Chen, X. Chen, X. M. Cai, S. Huang, F. Wang, *ACS Sustainable Chemistry & Engineering*, 2018, **6**, 2898-2904, doi: 10.1021/acssuschemeng.7b04491.
- [48] T. Budtova, *Cellulose*, 2019, **26**, 81-121, doi: 10.1007/s10570-018-2189-1.
- [49] J. Fan, Z. Shi, L. Zhang, J. Wang, J. Yin, *Nanoscale*, 2012, **4**, 7046, doi: 10.1039/c2nr31907a.
- [50] M. Yang, K. Cao, L. Sui, Y. Qi, J. Zhu, A. Waas, E. M. Arruda, J. Kieffer, M. D. Thouless, N. A. Kotov, *ACS Nano*, 2011, **5**, 6945-6954, doi: 10.1021/nn2014003.
- [51] J. Lyu, Z. Liu, X. Wu, G. Li, D. Fang, X. Zhang, *ACS Nano*, 2019, **13**, 2236-2245, doi: 10.1021/acsnano.8b08913.
- [52] R. Liu, J. Wang, J. Liao, X. Zhang, *Frontiers in Materials*, 2021, **8**, 659655, doi: 10.3389/fmats.2021.659655.
- [53] Y. Xiao, L. Li, S. Zhang, J. Feng, Y. Jiang, J. Feng, *Advanced Engineering Materials*, 2021, **23**, 2000856, doi: 10.1002/adem.202000856.
- [54] M. Pantoja, N. Boynton, K. A. Cavicchi, B. Dosa, J. L. Cashman, M. A. B. Meador, *ACS Applied Materials & Interfaces*, 2019, **11**, 9425-9437, doi: 10.1021/acsami.8b20420.
- [55] J. Feng, X. Wang, Y. Jiang, D. Du, J. Feng, *ACS Applied Materials & Interfaces*, 2016, **8**, 12992-12996, doi: 10.1021/acsami.6b02183.
- [56] X. Li, J. Wang, Y. Zhao, X. Zhang, *Journal of Applied Polymer Science*, 2020, **137**, 48849, doi: 10.1002/app.48849.
- [57] Z. Liu, J. Lyu, D. Fang, X. Zhang, *ACS Nano*, 2019, **13**, 5703-5711, doi: 10.1021/acsnano.9b01094.
- [58] X. Li, J. Wang, Y. Zhao, X. Zhang, *ACS Applied Materials & Interfaces*, 2018, **10**, 16901-16910, doi: 10.1021/acsami.8b04081.
- [59] X. Ji, H. Zhang, Z. Bai, G. Qiu, M. Guo, F. Cheng, M. Zhang, *Energy and Buildings*, 2019, **205**, 109533, doi: 10.1016/j.enbuild.2019.109533.
- [60] S. F. Wang, J. Zhang, D. W. Luo, F. Gu, D. Y. Tang, Z. L. Dong, G. E. B. Tan, W. X. Que, T. S. Zhang, S. Li, L. B. Kong, *Progress in Solid State Chemistry*, 2013, **41**, 20-54, doi: 10.1016/j.progsolidstchem.2012.12.002.
- [61] L. Boatema, C. Kwakernaak, S. van der Zwaag, W. G. Sloof, *Journal of the European Ceramic Society*, 2016, **36**, 4141-4145, doi: 10.1016/j.jeurceramsoc.2016.05.038.
- [62] G. Zu, K. Kanamori, K. Nakanishi, J. Huang, *Chemistry of Materials*, 2019, **31**, 6276-6285, doi: 10.1021/acs.chemmater.9b02437.
- [63] G. Zu, K. Kanamori, X. Wang, K. Nakanishi, J. Shen, *Chemistry of Materials*, 2020, **32**, 1595-1604, doi: 10.1021/acs.chemmater.9b04877.
- [64] G. Zu, K. Kanamori, T. Shimizu, Y. Zhu, A. Maeno, H. Kaji, K. Nakanishi, J. Shen, *Chemistry of Materials*, 2018, **30**, 2759-2770, doi: 10.1021/acs.chemmater.8b00563.
- [65] G. Zu, K. Kanamori, A. Maeno, H. Kaji, K. Nakanishi, *Angewandte Chemie International Edition*, 2018, **57**, 9722-9727, doi: 10.1002/anie.201804559.
- [66] G. Liu, B. Zhou, A. Du, J. Shen, G. Wu, *Colloid. Surface A*, 2013, **436**, 763-774, doi: 10.1016/j.colsurfa.2013.08.003.
- [67] A. Du, H. Wang, B. Zhou, C. Zhang, X. Wu, Y. Ge, T. Niu, X. Ji, T. Zhang, Z. Zhang, G. Wu, J. Shen, *Chemistry of Materials*, 2018, **30**, 6849-6857, doi: 10.1021/acs.chemmater.8b02926.
- [68] F. Peng, Y. Jiang, J. Feng, H. Cai, J. Feng, L. Li, *Chemical*

- Engineering Journal*, 2021, **411**, 128402, doi: 10.1016/j.cej.2021.128402.
- [69] C. M. R. Almeida, M. E. Ghica, L. Durães, *Advances in Colloid and Interface Science*, 2020, **282**, 102189, doi: 10.1016/j.cis.2020.102189.
- [70] G. Zu, J. Shen, L. Zou, W. Wang, Y. Lian, Z. Zhang, A. Du, *Chemistry of Materials*, 2013, **25**, 4757-4764, doi: 10.1021/cm402900y.
- [71] E. Zhang, W. Zhang, T. Iv, J. Li, J. Dai, F. Zhang, Y. Zhao, J. Yang, W. Li, H. Zhang, *ACS Applied Materials & Interfaces*, 2021, **13**, 20548-20558, doi: 10.1021/acsami.1c02501.
- [72] X. Zhang, T. Zhang, Z. Yi, L. Yan, S. Liu, X. Yao, A. Guo, J. Liu, F. Hou, *Ceramics International*, 2020, **46**, 28561-28568, doi: 10.1016/j.ceramint.2020.08.013.
- [73] S. S. Kistler, *Nature*, 1931, **127**, 741-741 doi: 10.1021/j150331a003.
- [74] A. Feinle, M. S. Elsaesser, N. Hüsing, *Chemical Society Reviews*, 2016, **45**, 3377-3399, doi: 10.1039/c5cs00710k.
- [75] V. Baudron, P. Gurikov, I. Smirnova, S. Whitehouse, *Gels*, 2019, **5**, 12, doi: 10.3390/gels5010012.
- [76] L. Dou, X. Zhang, X. Cheng, Z. Ma, X. Wang, Y. Si, J. Yu, B. Ding, *ACS Applied Materials & Interfaces*, 2019, **11**, 29056-29064, doi: 10.1021/acsami.9b10018.
- [77] X. Zhang, F. Wang, L. Dou, X. Cheng, Y. Si, J. Yu, B. Ding, *ACS Nano*, 2020, **14**, 15616-15625, doi: 10.1021/acsnano.0c06423.
- [78] C. Vakifahmetoglu, D. Zeydanli, P. Colombo, *Materials Science and Engineering: R: Reports*, 2016, **106**, 1-30, doi: 10.1016/j.mser.2016.05.001.
- [79] T.-D. Nguyen, D. Tang, F. D'Acierno, C. A. Michal, M. J. MacLachlan, *Chemistry of Materials*, 2018, **30**, 1602-1609, doi: 10.1021/acs.chemmater.7b04800.
- [80] G. Nyström, L. Roder, M. P. Fernández-Ronco, R. Mezzenga, *Advanced Functional Materials*, 2018, **28**, 1703609, doi: 10.1002/adfm.201703609.
- [81] X. Wang, J. Liu, F. Hou, X. Lu, X. Sun, Y. Zhou, *Journal of the European Ceramic Society*, 2015, **35**, 1751-1759, doi: 10.1016/j.jeurceramsoc.2014.12.033.
- [82] T.-D. Nguyen, W. Y. Hamad, M. J. MacLachlan, *Materials Chemistry Frontiers*, 2018, **2**, 1655-1663, doi: 10.1039/c8qm00200b.
- [83] W. Xu, A. Du, J. Xiong, Z. Zhang, J. Shen, B. Zhou, *Materials & Design*, 2016, **97**, 93-97, doi: 10.1016/j.matdes.2016.02.070.
- [84] J. Zhou, B. Wei, Z. Yao, H. Lin, R. Tan, W. Chen, X. Guo, *Journal of Alloys and Compounds*, 2020, **819**, 153021, doi: 10.1016/j.jallcom.2019.153021.
- [85] X. Wang, L. Dou, Z. Li, L. Yang, J. Yu, B. Ding, *ACS Applied Materials & Interfaces*, 2016, **8**, 34668-34676, doi: 10.1021/acsami.6b11294.
- [86] F. Wang, J. Dai, L. Huang, Y. Si, J. Yu, B. Ding, *ACS Nano*, 2020, **14**, 8975-8984, doi: 10.1021/acsnano.0c03793.
- [87] Y. Si, X. Wang, C. Yan, L. Yang, J. Yu, B. Ding, *Advanced Materials*, 2016, **28**, 9512-9518, doi: 10.1002/adma.201603143.
- [88] Y. Xie, L. Wang, Y. Peng, D. Ma, L. Zhu, G. Zhang, X. Wang, *Chemical Engineering Journal*, 2021, **416**, 128994, doi: 10.1016/j.cej.2021.128994.
- [89] X. Wu, L. Cao, J. Song, Y. Si, J. Yu, B. Ding, *Journal of Colloid and Interface Science*, 2020, **560**, 681-689, doi: 10.1016/j.jcis.2019.10.119.
- [90] Y. Cai, J. Song, X. Liu, X. Yin, X. Li, J. Yu, B. Ding, *Environmental Science: Nano*, 2018, **5**, 2631-2640, doi: 10.1039/c8en00866c.
- [91] A. Y. Malkin, A. V. Semakov, I. Y. Skvortsov, P. Zatonskikh, V. G. Kulichikhin, A. V. Subbotin, A. N. Semenov, *Macromolecules*, 2017, **50**, 8231-8244, doi: 10.1021/acs.macromol.7b00687.
- [92] E. Hofmann, K. Krüger, C. Haynl, T. Scheibel, M. Trebbin, S. Förster, *Lab on a Chip*, 2018, **18**, 2225-2234, doi: 10.1039/c8lc00304a.
- [93] A. Magaz, A. D. Roberts, S. Faraji, T. R. L. Nascimento, E. S. Medeiros, W. Zhang, R. D. Greenhalgh, A. Mautner, X. Li, J. J. Blaker, *Biomacromolecules*, 2018, **19**, 4542-4553, doi: 10.1021/acs.biomac.8b01233.
- [94] M. Gonzalez-Abrego, A. Hernandez-Granados, C. Guerrero-Bermea, A. Martinez de la Cruz, D. Garcia-Gutierrez, S. Sepulveda-Guzman, R. Cruz-Silva, *Journal of Sol-Gel Science and Technology*, 2017, **81**, 468-474, doi: 10.1007/s10971-016-4210-1.
- [95] J. L. Daristotle, A. M. Behrens, A. D. Sandler, P. Kofinas, *ACS Applied Materials & Interfaces*, 2016, **8**, 34951-34963, doi: 10.1021/acsami.6b12994.
- [96] Y. Gao, J. Zhang, Y. Su, H. Wang, X.-X. Wang, L.-P. Huang, M. Yu, S. Ramakrishna, Y.-Z. Long, *Materials Horizons*, 2021, **8**, 426-446, doi: 10.1039/d0mh01096k.
- [97] C. Xu, H. Wang, J. Song, X. Bai, Z. Liu, M. Fang, Y. Yuan, J. Sheng, X. Li, N. Wang, H. Wu, *Journal of the American Ceramic Society*, 2018, **101**, 1677-1683, doi: 10.1111/jace.15301.
- [98] H. Wang, S. Lin, S. Yang, X. Yang, J. Song, D. Wang, H. Wang, Z. Liu, B. Li, M. Fang, N. Wang, H. Wu, *Small*, 2018, **14**, 1800258, doi: 10.1002/smll.201800258.
- [99] C. Jia, L. Li, Y. Liu, B. Fang, H. Ding, J. Song, Y. Liu, K. Xiang, S. Lin, Z. Li, W. Si, B. Li, X. Sheng, D. Wang, X. Wei, H. Wu, *Nature Communications*, 2020, **11**, 3732, doi: 10.1038/s41467-020-17533-6.
- [100] H. Wang, X. Zhang, N. Wang, Y. Li, X. Feng, Y. Huang, C. Zhao, Z. Liu, M. Fang, G. Ou, H. Gao, X. Li, H. Wu, *Science Advances*, 2017, **3**, e1603170, doi: 10.1126/sciadv.1603170.
- [101] L. Su, H. Wang, M. Niu, X. Fan, M. Ma, Z. Shi, S. W. Guo, *ACS Nano*, 2018, **12**, 3103-3111, doi: 10.1021/acsnano.7b08577.
- [102] L. Su, M. Li, H. Wang, M. Niu, D. Lu, Z. Cai, *ACS Applied Materials & Interfaces*, 2019, **11**, 15795-15803, doi: 10.1021/acsami.9b02869.
- [103] D. Lu, L. Su, H. Wang, M. Niu, L. Xu, M. Ma, H. Gao, Z. Cai, X. Fan, *ACS Applied Materials & Interfaces*, 2019, **11**, 45338-45344, doi: 10.1021/acsami.9b16811.
- [104] A. Soleimani Dorcheh, M. H. Abbasi, *Journal of Materials Processing Technology*, 2008, **199**, 10-26, doi: 10.1016/j.jmatprotec.2007.10.060.
- [105] J. Wang, Y. Zhang, X. Zhang, *Journal of Materials*

- Chemistry A*, 2016, **4**, 11408-11415, doi: 10.1039/c6ta04306b.
- [106] J. Wang, Y. Zhang, Y. Wei, X. Zhang, *Microporous and Mesoporous Materials*, 2015, **218**, 192-198, doi: 10.1016/j.micromeso.2015.07.019.
- [107] J. Wang, Y. Wei, W. He, X. Zhang, *RSC Advances*, 2014, **4**, 51146-51155, doi: 10.1039/c4ra10607e.
- [108] Y. Zhang, J. Wang, Y. Wei, X. Zhang, *New Journal of Chemistry*, 2017, **41**, 1953-1958, doi: 10.1039/c6nj03414d.
- [109] Z. Chen, Y. Zhao, X. Zhu, *ACS Applied Materials & Interfaces*, 2021, **13**, 12230-12240, doi: 10.1021/acsami.1c00205.
- [110] N. Bheekhun, A. R. Abu Talib, M. R. Hassan, *Advances in Materials Science and Engineering*, 2013, **2013**, 1-18, doi: 10.1155/2013/406065.
- [111] J. Stergar, U. Maver, *Journal of Sol-Gel Science and Technology*, 2016, **77**, 738-752, doi: 10.1007/s10971-016-3968-5.
- [112] P. Wang, M. Du, H. Zhu, S. Bao, T. Yang, M. Zou, *Journal of hazardous materials*, 2015, **286**, 533-44, doi: 10.1016/j.jhazmat.2014.12.034.
- [113] M. Gao, B. Liu, P. Zhao, X. Yi, X. Shen, Y. Xu, *Journal of Sol-Gel Science and Technology*, 2019, **91**, 514-522, doi: 10.1007/s10971-019-05057-5.
- [114] A. Lecomte, F. Blanchard, A. Dager, M. C. Silva, R., *Journal of Non-Crystalline Solids*, 1998, **225**, 120-124, doi: 10.1016/s0022-3093(98)00107-0.
- [115] Q. Sun, Y. L. Zhang, J. F. Deng, S. Y. Chen, D. Wu, *Applied Catalysis A: General*, 1997, **152**, L165-L171, doi: 10.1016/S0926-860X(96)00354-7.
- [116] F. I. Hurwitz, R. B. Rogers, H. Guo, A. Garg, N. S. Olson, D. Phan, J. L. Cashman, *Journal of the American Ceramic Society*, 2020, **103**, 6700-6711, doi: 10.1111/jace.17376.
- [117] K. K. Kim, A. Hsu, X. Jia, S. M. Kim, Y. Shi, M. Dresselhaus, T. Palacios, J. Kong, *ACS Nano*, 2012, **6**, 8583-8590, doi: 10.1021/nn301675f.
- [118] L. Wang, Z. Chen, C. R. Dean, T. Taniguchi, K. Watanabe, L. E. Brus, J. Hone, *ACS Nano*, 2012, **6**, 9314-9319, doi: 10.1021/nn304004s.
- [119] M. Streit, F. Ingold, *Journal of the European Ceramic Society*, 2005, **25**, 2687-2692, doi: 10.1016/j.jeurceramsoc.2005.03.181.
- [120] M. Koebel, A. Rigacci, P. Achard, *Journal of Sol-Gel Science and Technology*, 2012, **63**, 315-339, doi: 10.1007/s10971-012-2792-9.
- [121] R. Baetens, B. P. Jelle, A. Gustavsen, *Energy and Buildings*, 2011, **43**, 761-769, doi: 10.1016/j.enbuild.2010.12.012.
- [122] T. Sainsbury, T. Ikuno, D. Okawa, D. Pacile', Jean M. J. Fre'chet, A. Zettl, *The Journal of Physical Chemistry C*, 2017, **111**, 12992-12999, doi: 10.1021/jp072958n.
- [123] R. W. Cahn, *Nature*, 1988, **332**, 112-113, doi: 10.1038/332112a0.
- [124] Y. Chen, J. Zou, S. J. Campbell, G. Le Caer, *Applied Physics Letters*, 2004, **84**, 2430-2432, doi: 10.1063/1.1667278.
- [125] L. Fu, T. Wang, J. Yu, W. Dai, H. Sun, Z. Liu, R. Sun, N. Jiang, A. Yu, C. T. Lin, *2D Materials*, 2017, **4**, 025047, doi: 10.1088/2053-1583/aa636e.
- [126] J. Wang, F. Ma, M. Sun, *RSC Advances*, 2017, **7**, 16801-16822, doi: 10.1039/c7ra00260b.
- [127] C. G. Cofer, J. Economy, *Carbon*, 1995, **33**, 389-395, doi: 10.1016/0008-6223(94)00163-t.
- [128] T. Pham, A. P. Goldstein, J. P. Lewicki, S. O. Kucheyev, C. Wang, T. P. Russell, M. A. Worsley, L. Woo, W. Mickelson, A. Zettl, *Nanoscale*, 2015, **7**, 10449-10458, doi: 10.1039/c5nr01672j.
- [129] X. Xu, Q. Zhang, M. Hao, *Science*, 2019, **363**, 723-727, doi: 10.1126/science.aav7304.
- [130] Y. Si, J. Yu, X. Tang, J. Ge, B. Ding, *Nature Communications*, 2014, **5**, 5802, doi: 10.1038/ncomms6802.
- [131] D. Xia, H. Li, P. Huang, J. Mannering, U. Zafar, D. Baker, R. Menzel, *Journal of Materials Chemistry A*, 2019, **7**, 24027-24037, doi: 10.1039/c9ta06599g.
- [132] H. Yang, C. Li, X. Yue, J. Huo, F. Ye, J. Liu, F. Shi, J. Ma, *Materials & Design*, 2020, **185**, 108217, doi: 10.1016/j.matdes.2019.108217.
- [133] W. Wang, Y. Cheng, G. Ma, G. Tan, X. Sun, S. Yang, *Applied Sciences*, 2018, **9**, 60, doi: 10.3390/app9010060.
- [134] P. M. Rewatkar, T. Taghvace, A. M. Saeed, S. Donthula, C. Mandal, N. Chandrasekaran, T. Leventis, T. K. Shruthi, C. Sotiriou-Leventis, N. Leventis, *Chemistry of Materials*, 2018, **30**, 1635-1647, doi: 10.1021/acs.chemmater.7b04981.
- [135] Y. Kong, J. Zhang, Z. Zhao, X. Jiang, X. Shen, *Ceramics International*, 2019, **45**, 16331-16337, doi: 10.1016/j.ceramint.2019.05.160.
- [136] P. Colombo, G. Mera, R. Riedel, G. D. Sorarù, *Journal of the American Ceramic Society*, 2010, **93**, 1805-1837, doi: 10.1111/j.1551-2916.2010.03876.x.
- [137] C. Song, Y. Liu, F. Ye, J. Wang, L. Cheng, *Ceramics International*, 2020, **46**, 7719-7732, doi: 10.1016/j.ceramint.2019.11.275.
- [138] H. Tian, H. Fan, J. Ma, Z. Liu, L. Ma, S. Lei, J. Fang, C. Long, *Journal of Hazardous Materials*, 2018, **341**, 102-111, doi: 10.1016/j.jhazmat.2017.07.056.
- [139] X. Gao, J. Feng, D. Su, Y. Ma, G. Wang, H. Ma, J. Zhang, *Nano Energy*, 2019, **59**, 598-609, doi: 10.1016/j.nanoen.2019.03.016.
- [140] N. Leventis, A. Sadekar, N. Chandrasekaran, C. Sotiriou-Leventis, *Chemistry of Materials*, 2010, **22**, 2790-2803, doi: 10.1021/cm903662a.
- [141] W. Lu, E. S. Steigerwalt, J. T. Moore, L. M. Sullivan, E. W. Collins, C. M. Lukehart, *Journal of Nanoscience and Nanotechnology*, 2004, **4**, 803-808, doi: 10.1166/jnn.2004.119.
- [142] X. K. Li, L. Liu, Y. X. Zhang, S. D. Shen, S. Ge, L. C. Ling, *Carbon*, 2001, **39**, 159-165, doi: 10.1016/s0008-6223(00)00020-8.
- [143] K. Chen, X. Huang, Z. Zhang, A. Du, B. Zhou, Y. Xu, Z. Zhou, Y. Wang, *Journal of Materials Chemistry A*, 2015, **3**, 11745-11749, doi: 10.1039/c5ta00427f.
- [144] Y. Katoh, K. Ozawa, C. Shih, T. Nozawa, R. J. Shinavski, A. Hasegawa, L. L. Snead, *Journal of Nuclear Materials*, 2014, **448**, 448-476, doi: 10.1016/j.jnucmat.2013.06.040.
- [145] S. Nekahi, M. Vajdi, F. Sadegh Moghanlou, K. Vaferi, A.

- Motallebzadeh, M. Özen, U. Aydemir, J. Sha, M. Shahedi Asl, *Ceramics International*, 2019, **45**, 19060-19067, doi: 10.1016/j.ceramint.2019.06.150.
- [146] M. A. Farrokhzad, T. I. Khan, *Oxidation of Metals*, 2016, **86**, 431-451, doi: 10.1007/s11085-016-9645-9.
- [147] Lin FP, Du Y, Lv J, Zhang C, Liu X, T. ZP, *International Journal of Materials Research*, 2020, **6**, 479-490, doi: 10.3139/146.111907.
- [148] W. G. Fahrenholtz, G. E. Hilmas, *Scripta Materialia*, 2017, **129**, 94-99, doi: 10.1016/j.scriptamat.2016.10.018.
- [149] B. Ma, W. Han, E. Guo, *International Journal of Refractory Metals and Hard Materials*, 2014, **46**, 159-167, doi: 10.1016/j.ijrmhm.2014.05.013.
- [150] Y. Kubota, H. Tanaka, Y. Arai, R. Inoue, Y. Kogo, K. Goto, *Journal of the European Ceramic Society*, 2017, **37**, 1187-1194, doi: 10.1016/j.jeurceramsoc.2016.10.034.
- [151] Z. Zhang, D. M. Y. Lai, S. H. Lim, H. Jin, S. Wang, J. Chai, J. Pan, *Journal of Alloys and Compounds*, 2019, **790**, 536-546, doi: 10.1016/j.jallcom.2019.03.236.
- [152] Bill J, A. F, *Advanced Materials*, 1995, **7**, 775-787, doi: 10.1002/adma.19950070903.
- [153] Pampuch R, S. L, *Ceramics international*, 1991, **17**, 69-77, doi: 10.1016/0272-8842(91)90013-P.
- [154] K. Chen, Z. Bao, A. Du, X. Zhu, G. Wu, J. Shen, B. Zhou, *Microporous and Mesoporous Materials*, 2012, **149**, 16-24, doi: 10.1016/j.micromeso.2011.09.008.
- [155] C. Ferraro, E. Garcia-Tuñón, V. G. Rocha, S. Barg, M. D. Fariñas, T. E. G. Alvarez-Arenas, G. Sernicola, F. Giuliani, E. Saiz, *Advanced Functional Materials*, 2016, **26**, 1636-1645, doi: 10.1002/adfm.201504051.
- [156] Y. Chen, O. Ola, H. Chen, N. Wang, Y. Xia, Y. Zhu, *ACS Applied Nano Materials*, 2019, **2**, 7540-7548, doi: 10.1021/acsanm.9b01590.
- [157] T. Niu, B. Zhou, Z. Zhang, X. Ji, J. Yang, Y. Xie, H. Wang, A. Du, *Nanomaterials*, 2020, **10**, 2527, doi: 10.3390/nano10122527.
- [158] J. Zhang, Y. Cheng, M. Tebyetekerwa, S. Meng, M. Zhu, Y. Lu, *Advanced Functional Materials*, 2019, **29**, 1806407, doi: 10.1002/adfm.201806407.
- [159] W. Zou, X. Wang, Y. Wu, L. Zou, G. Zu, D. Chen, J. Shen, *Ceramics International*, 2019, **45**, 644-650, doi: 10.1016/j.ceramint.2018.09.223.
- [160] R. Liu, X. Dong, S. Xie, T. Jia, Y. Xue, J. Liu, W. Jing, A. Guo, *Chemical Engineering Journal*, 2019, **360**, 464-472, doi: 10.1016/j.cej.2018.12.018.
- [161] Y. Mizushima, M. Hori, *Journal of Materials Research*, 1993, **8**, 2993-2999, doi: 10.1557/jmr.1993.2993.
- [162] Z. Zhang, Q. Gao, Y. Liu, C. Zhou, M. Zhi, Z. Hong, F. Zhang, B. Liu, *RSC Advances*, 2015, **5**, 84280-84283, doi: 10.1039/c5ra13999f.
- [163] Z. Shi, H. Gao, X. Wang, C. Li, W. Wang, Z. Hong, M. Zhi, *Microporous and Mesoporous Materials*, 2018, **259**, 26-32, doi: 10.1016/j.micromeso.2017.09.025.
- [164] C. Jia, Y. Liu, L. Li, J. Song, H. Wang, Z. Liu, Z. Li, B. Li, M. Fang, H. Wu, *Nano Letters*, 2020, **20**, 4993-5000, doi: 10.1021/acs.nanolett.0c01107.
- [165] H. Yu, Y. Jiang, Y. Lu, X. Li, H. Zhao, Y. Ji, M. Wang, *Journal of Non-Crystalline Solids*, 2019, **505**, 79-86, doi: 10.1016/j.jnoncrysol.2018.10.039.
- [166] B. X. Zhang, Y. Zhang, Z. Luo, W. Han, W. Qiu, T. Zhao, *ACS Omega*, 2018, **3**, 4688-4694, doi: 10.1021/acsomega.8b00098.
- [167] G. Li, M. Zhu, W. Gong, R. Du, A. Eychmüller, T. Li, W. Lv, X. Zhang, *Advanced Functional Materials*, 2019, **29**, 1900188, doi: 10.1002/adfm.201900188.
- [168] J. T. Cahill, S. Turner, J. Ye, B. Shevitski, S. Aloni, T. F. Baumann, A. Zettl, J. D. Kuntz, M. A. Worsley, *Chemistry of Materials*, 2019, **31**, 3700-3704, doi: 10.1021/acs.chemmater.9b00496.
- [169] F. Li, J. X. Liu, X. Huang, W. Bao, G. J. Zhang, H. Wang, *Journal of the American Ceramic Society*, 2019, **102**, 5746-5762, doi: 10.1111/jace.16488.
- [170] J. W. Long, C. N. Chervin, R. B. Balow, S. Jeon, J. B. Miller, M. E. Helms, J. C. Owrutsky, D. R. Rolison, K. P. Fears, *Industrial & Engineering Chemistry Research*, 2020, **59**, 19584-19592, doi: 10.1021/acs.iecr.0c02983.
- [171] I. Mejri, M. K. Younes, A. Ghorbel, *Journal of Sol-Gel Science and Technology*, 2006, **40**, 3-8, doi: 10.1007/s10971-006-9114-z.
- [172] A. Benad, F. Jürries, B. Vetter, B. Klemmed, R. Hübner, C. Leyens, A. Eychmüller, *Chemistry of Materials*, 2018, **30**, 145-152, doi: 10.1021/acs.chemmater.7b03911.
- [173] T. Kidchob, L. Malfatti, F. Serra, P. Falcaro, S. Enzo, P., *Journal of Sol-Gel Science and Technology*, 2007, **42**, 89-93, doi: 10.1007/s10971-006-1511-9.
- [174] M. Zhang, Y. Wang, Y. Zhang, J. Song, Y. Si, J. Yan, C. Ma, Y. T. Liu, J. Yu, B. Ding, *Angewandte Chemie International Edition*, 2020, **59**, 23252-23260, doi: 10.1002/anie.202010110.
- [175] M. Popa, D. Macovei, E. Indrea, I. Mercioniu, I. C. Popescu, V. Danciu, *Microporous and Mesoporous Materials*, 2010, **132**, 80-86, doi: 10.1016/j.micromeso.2009.12.024.
- [176] B. Wang, Y. Niu, S. Zheng, Y. Yin, M. Ding, *IEEE Photonics Technology Letters*, 2020, **32**, 89-92, doi: 10.1109/lpt.2019.2957917.
- [177] Z. He, C. Li, C. Chen, Y. Tong, T. Luo, Z. Zhan, *Journal of Power Sources*, 2018, **392**, 200-205, doi: 10.1016/j.jpowsour.2018.04.085.
- [178] Q. Wang, Z. Liu, Y. Wang, Y. Sun, Y. Gong, *International Journal of Refractory Metals and Hard Materials*, 2018, **77**, 132-140, doi: 10.1016/j.ijrmhm.2018.08.007.
- [179] R. Yang, F. Hu, L. An, J. Armstrong, Y. Hu, C. Li, Y. Huang, S. Ren, *Nano Letters*, 2020, **20**, 1110-1116, doi: 10.1021/acs.nanolett.9b04411.
- [180] H. Cheng, H. Xue, C. Hong, X. Zhang, *Composites Science and Technology*, 2017, **140**, 63-72, doi: 10.1016/j.compscitech.2016.12.031.
- [181] R. D. Lorenz, *Powder Technology*, 2019, **355**, 264-267, doi: 10.1016/j.powtec.2019.07.057.
- [182] H. Jin, X. Zhou, T. Xu, C. Dai, Y. Gu, S. Yun, T. Hu, G. Guan, J. Chen, *ACS Applied Materials & Interfaces*, 2020, **12**,

11815-11824, doi: 10.1021/acsami.9b20923.

[183] B. N. Nguyen, M. A. B. Meador, D. Scheiman, L. McCorkle, *ACS Applied Materials & Interfaces*, 2017, **9**, 27313-27321, doi: 10.1021/acsami.7b07821.

[184] J. P. Randall, M. A. B. Meador, S. C. Jana, *ACS Applied Materials & Interfaces*, 2011, **3**, 613-626, doi: 10.1021/am200007n.

[185] Y. Chen, Y. Chen, D. Ding, Y. Ding, Y. Choi, L. Zhang, S. Yoo, D. Chen, B. De Glee, H. Xu, Q. Lu, B. Zhao, G. Vardar, J. Wang, H. Bluhm, E. J. Crumlin, C. Yang, J. Liu, B. Yildiz, M. Liu, *Energy & Environmental Science*, 2017, **10**, 964-971, doi: 10.1039/c6ee03656b.

[186] Z. Gao, L. V. Moggi, E. C. Miller, J. G. Railsback, S. A. Barnett, *Energy & Environmental Science*, 2016, **9**, 1602-1644, doi: 10.1039/c5ee03858h.

[187] Y. Fu, G. Wang, X. Ming, X. Liu, B. Hou, T. Mei, J. Li, J. Wang, X. Wang, *Carbon*, 2018, **130**, 250-256, doi: 10.1016/j.carbon.2017.12.124.

[188] V. Adavan Kiliyankil, B. Fugetsu, I. Sakata, Z. Wang, M. Endo, *Journal of Colloid and Interface Science*, 2021, **582**, 950-960, doi: 10.1016/j.jcis.2020.08.100.

[189] F. Y. Zeng, Z. Y. Sui, S. Liu, H. P. Liang, H. H. Zhan, B. H. Han, *Materials Today Communications*, 2018, **16**, 1-7, doi: 10.1016/j.mtcomm.2018.03.015.

[190] Y. Song, B. Li, S. Yang, G. Ding, C. Zhang, X. Xie, *Scientific Reports*, 2015, **5**, 10337, doi: 10.1038/srep10337.

[191] D. Ishutenko, Y. Anashkin, P. Nikulshin, *Applied Catalysis B: Environmental*, 2019, **259**, 118041, doi: 10.1016/j.apcatb.2019.118041.

[192] A. Wang, J. Li, T. Zhang, *Nature Reviews Chemistry*, 2018, **2**, 65-81, doi: 10.1038/s41570-018-0010-1.

[193] F. Caddeo, D. Loche, M. F. Casula, A. Corrias, *Frontiers in Chemistry*, 2020, **8**, 57, doi: 10.3389/fchem.2020.00057.

[194] C. Liang, Z. Wang, L. Wu, X. Zhang, H. Wang, Z. Wang, *ACS Applied Materials & Interfaces*, 2017, **9**, 29950-29957, doi: 10.1021/acsami.7b07735.

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