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Short communication

Thermally conductive SiC as support of aluminum fluoride for the catalytic dehydrofluorination reaction



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<i>Keywords:</i> Silicon carbide Aluminum fluoride Thermal conductivity Dehydrofluorination	Aluminum fluoride (AlF ₃) is a typical catalyst for dehydrofluorination of hydrofluorocarbons (HFCs) to fluoroolefins with high heat of reaction. Consequently, heat supply and sintering are the key challenges for AlF ₃ -based catalysts. Herein, SiC with high thermal conductivity and resistance to HF corrosion is suggested as a candidate support of AlF ₃ catalyst. The interaction between AlF ₃ and SiC leads to uniform distribution of the catalytic phase, and as a result of this, AlF ₃ /SiC exhibits high catalytic activity and stability for the dehydro-fluorination of 1,1-difluoroethane to vinyl fluoride. This study proposes a novel catalyst support (SiC) for strong endothermic catalytic reactions involving HFCs for the first time to the best of our knowledge.

1. Introduction

Global warming has been one of the major challenges for the whole society which is attracting increasing attention recently [1]. In addition to CO₂, typical greenhouse gases, hydrofluorocarbons (HFCs) also play a significant role with increasing emissions, which are usually of high global warming potential (GWP) [2]. For instance, the GWP of 1,1-difluoroethane (HFC-152a) is 1300 times larger than that of CO_2 [3]. The emission of these gases is regulated by the Montreal Protocol and its amendments, especially the recent Kigali Amendment [4]. As reported in the literature [5-7], dehydrofluorination of HFCs to hydrofluoroolefins (HFOs), the monomers used for manufacturing various fluorinated polymers, is the most efficient route for converting these greenhouse gases into value-added and environmentally benign chemicals.

Besides, dehydrofluorination of HFC-152a can benefit the manufacturing of polyvinyl fluoride (PVF), which is a typical polymer material with excellent resistance to weathering, chemically inert nature, suitable mechanical strength, low permeability and light transmittance [8,9], and it is widely adopted in packaging, glazing and electrical applications [10]. At present, as the feedstock of PVF, the monomer of vinyl fluoride (VF) is mainly produced via hydrofluorination of acetylene and dehydrofluorination of HFC-152a. During the hydrofluorination of acetylene, HFC-152a would be generated as the byproduct with large quantity [3,11]. Consequently, dehydrofluorination of HFC-152a plays an important role in the preparation of VF.

stability However, due to the high of C-F bond, dehydrofluorination of hydrofluorocarbons (HFCs) is hindered both thermodynamically and kinetically [12]. Therefore, it necessitates the development of effective and proper catalysts. It is well accepted that the catalysts should be Lewis acid catalysts, including fluorinated Cr, Al and Mg-based catalysts. However, strong Lewis acid catalysts usually suffer from coke formation [13]. Clearly, the Lewis acid sites function as both active sites and coking sites leading to catalyst deactivation. As a response to this, pre-deposition of carbon over the AlF₃ catalyst before reaction can improve significantly the stability for dehydrofluorination of 1, 1, 1, 3, 3-pentafluoropropane [14]. Moreover, besides the fluorinated monomers, HF is also the major product of the dehydrofluorination of HFCs. Due to the presence of the highly corrosive HF, there is very few choices left for the development of dehydrofluorination catalysts.

In addition to the challenge in selecting appropriate catalytic materials, heat transfer is another problem for dehydrofluorination reactions. Clearly, the dehydrofluorination catalytic process includes the cleavage of extremely stable C-F bonds with dissociation energies higher than 450 kJ mol $^{-1}$, which is one of the highest bond energies. As a result, all the dehydrofluorination reactions are highly endothermic. In order to provide enough heat to the reaction zone, superheated steam or excessive dilution of N₂ was preferred for the pyrolysis of HFCs and HCFCs [15]. In the case of catalytic pyrolysis of HFCs, it will be favorable for the catalyst to be a very good thermally conductive material.

Silicon carbide (SiC) is a typical ceramic material with strong corrosion resistance, and high thermal conductivity [16]. Due to its

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excellent stability and thermal conductivity, SiC was considered as proper support of catalysts [17–20], and the catalytic selectivity and resistance to sintering of the supported active phase can be significantly improved [21]. In addition, SiC was found to be stable under the corrosion of HF acid [22]. Consequently, Al-based catalysts supported on SiC could be proposed that can effectively transfer heat to the reaction occurred on the supported phase, reduce the temperature of the catalyst bed, and prevent catalysts from sintering and carbon deposition at high reaction temperatures.

In this work, aluminum fluoride (AlF₃) supported on silicon carbide (SiC) was synthesized and evaluated as a highly efficient catalyst for the dehydrofluorination of HFC-152a toward fluoroolefins production. The catalytic activity and stability of carbon-supported AlF₃ (reference catalyst) were also investigated and compared with that of SiC-supported AlF₃.

2. Experimental

2.1. Reagents and chemicals

Silicon carbide (SiC, 99.0% with particle size between 0.5 and 0.7 μ m), aluminum nitrate (Al(NO₃)₃·9H₂O, > 98%) and ammonium fluoride (NH₄F, > 98%) were purchased from Aladdin Company, Shanghai, China. All other required chemicals with analytical purity were obtained from Sigma Aldrich, USA.

2.2. Synthesis of SiC-supported AlF₃ catalyst

Silicon carbide supported aluminum fluoride catalyst was prepared by the wet impregnation technique. 3 g of fine SiC powder was first gradually dried at 120 °C for 12 h in the oven. Then, 0.7124 g aluminum nitrate and 0.2132 g ammonium fluoride were dissolved in 3 mL deionized water. The obtained liquid mixture was then added dropwise and mixed with 3 g of fine SiC powder using a micropipette. After aging for 12 h, aluminum nitrate was fluorinated into aluminum fluoride. Finally, a homogeneous paste was obtained. The paste was initially dried at 120 °C and then annealed at 400 °C for 3 h in nitrogen gas atmosphere. As a reference, activated carbon-supported AlF_3 was prepared with exactly the same procedure.

2.3. Characterization of catalysts

The catalysts were characterized by powder X-ray diffraction (XRD) using a Thermo ARL X'TRA diffractometer (Cu-K α radiation, $\lambda = 0.154056$ nm) at room temperature, which was equipped with a Si (Li) solid detector at 40 kV/40 mA and a monochromator.

Transmission electron microscopy (TEM), energy dispersive X-ray spectrometry (EDXS) mapping and high-resolution transmission electron microscopy (HRTEM) images were recorded to further explore the microstructure of catalysts over a Tecnai G2 F30 S-Twin at 300 kV

(Philips-FEI Company).

Specific surface areas (m^2/g) of the supports were determined by the BET method making use of the N₂ adsorption isotherms at liquid nitrogen temperature (-195.7 °C) obtained using an Autosorb-1/C gas adsorption analyzer (Quantachrome Instruments).

X-ray photoelectron spectroscopy (XPS) measurements were performed on an ESCALAB210 (VG Co., monochromatized micro-focused Mg Ka X-ray source) to study the metal oxidation states and surface composition of the catalytic phase. Finally, solid state ²⁷Al NMR was adopted to explore better the structure of the catalysts.

2.4. Catalytic activity measurements

Catalytic activity measurements were carried out on a fixed bed reactor (stainless steel, 8 mm (i.d), L = 400 mm) under atmospheric pressure. The blank experiments (without a catalyst) showed no obvious reactions. Prior to the reaction, 2 mL of the catalyst (20–40 mesh) was loaded into the reactor and heated at 300 °C for 30 min in N₂ gas with a flow rate of 5 mL min⁻¹. Then, HFC-152a /N₂ gas mixture was fed into the reactor (HFC-152a/N₂ of 1/1, total flow rate of 10 mL min⁻¹, SV = 300 h⁻¹). The reaction products exit gas stream was passed through a KOH solution to trap HF, and then the gaseous products were analyzed by online gas chromatography (Fuli GC9790 chromatograph equipped with a PoraPLOT Q column and a TCD detector). Since the selectivity to VF was higher than 99.8% for all the catalysts, the selectivity data in dehydrofluorination activity test is not shown.

3. Results and discussion

According to reaction (1), simple dehydrofluorination of HFC-152a leads to the formation of vinyl fluoride (VF). After the removal of byproduct HF with water scrubber, almost pure VF would be obtained. However, due to the high stability of C–F bonds, no reaction was detected at elevated temperatures in the absence of catalyst. Clearly, it is necessary to develop a proper catalyst for this process. In addition, the enthalpy change of this reaction is as high as 84.4 kJ mol⁻¹. Consequently, heat supply for this reaction is another key challenge.

$$CH_3CHF_2 \rightarrow CH_2 = CHF + HF\Delta_r H_{298}^{\odot} = 84.4 \text{kJ} \text{ mol}^{-1}$$
(1)

As a response, SiC with high thermal conductivity and resistance to HF corrosion was selected as a support of AlF₃ catalyst for the first time to the best of our knowledge. As shown in Fig. 1a, no noticeable AlF₃ diffraction peaks were observed in the XRD pattern of 5 wt% AlF₃/SiC catalyst, in good agreement with the PDF card (74–1302) of cubic SiC (6H-SiC) without observing any other peaks. Clearly, SiC used in the present study was well crystalized. Since the detection limit of powder XRD for crystalline size determination is less than ~4 nm, the absence of AlF₃ diffraction peaks may suggest that AlF₃ was well dispersed on SiC. No change in the XRD pattern was noticed for the spent AlF₃/SiC



Fig. 1. XRD patterns of (a) fresh and spent 5 wt% AlF₃/SiC catalysts, (b) fresh and spent 5 wt% AlF₃/C catalysts.



Fig. 2. TEM images along with EDX elemental mapping. (a) AlF₃/SiC-fresh and (b) AlF₃/C-fresh catalysts.

catalyst (after reaction).

By contrast, clear AlF₃ diffraction peaks were detected over AlF₃/C indicating the formation of AlF₃ crystallites (Fig. 1b). Based on the XRD pattern, the crystal size of AlF₃ was determined to be 24.6 nm for the fresh AlF₃/C catalyst according to the Scherrer equation. After reaction, the crystal size of spent AlF₃/C increased to 28.7 nm, indicating significant sintering of AlF₃ over the activated carbon support.

Both AlF₃/SiC and AlF₃/C catalysts were further characterized by TEM and EDX mapping. As shown in Fig. 2, because of the poor contrast between AlF₃, SiC and activated carbon, no AlF₃ particles could be clearly observed in TEM images. However, with the help of EDX mapping, the elemental distribution could be completely disclosed. For the AlF₃/SiC catalyst, the elements including C, Si, Al and F were identified. Carbon (C) (Fig. 2a) and Si (Fig. S1) were observed all over the particle. In addition, Al and F were dispersed uniformly. The EDX spectra of the AlF₃/C showed the presence of C, F and Al (Fig. 2b). However, AlF₃ with large particle size was found with concentrated distribution of Al and F. The above results were well consistent with the observations from XRD. Clearly, the TEM examination and EDX elemental mapping results proved that the desired loading of AlF₃ had been successfully achieved.

After reaction, Si concentration in spent AlF₃/SiC catalyst was reduced significantly (Fig. S2), which can be attributed to coke deposition or etching of Si by HF during reaction. However, comparing the mapping of the C element in Fig. 2a and Fig. S2, only slight increase in C content can be noticed, while more AlF₃ (Al and F elements in Fig. S2) were exposed. Therefore, some of Si element can be etched by the HF product during the dehydrofluorination of HFC-152a. By contrast, carbon content increased significantly in spent AlF₃/C, while more sintered AlF₃ particles can be found (Fig. S3), indicating the coke formation on AlF₃/C during reaction. Elemental compositions of the fresh and spent 5 wt% AlF₃/C and 5 wt% AlF₃/SiC determined by mapping in Table S1 reinforce the above discussion.

As discussed previously, SiC is stable under the corrosion of HF [22]. We suggested that the etching of Si should not be contributed by SiC. As demonstrated in Fig. S4, significant amount of Si was fluorinated by NH_4F during catalyst preparation (XPS, binding energy of 102.3 eV), in addition to SiC (XPS, binding energy of 100.3 eV) [23].

Hence, SiC contains impurities such as Si and SiO_2 which are facilely fluorinated by fluorine -containing species.

The presence of AlF₃ over AlF₃/SiC and AlF₃/C catalysts is reinforced by HRTEM studies. Clear lattice fringes for both AlF₃/SiC and AlF₃/C catalysts were detected (Fig. S5). The lattice spacing of fringe along (200) direction is 0.35 nm, and that of fringe along (002) direction is 0.36 nm in the AlF₃ crystal structure [24]. Part of the AlF₃ crystals are highlighted with yellow circles (Fig. S5). As disclosed by HRTEM, the crystalline size of AlF₃ in the fresh AlF₃/SiC catalyst is ~6–8 nm, which is larger than the determination by XRD (Fig. S6a), probably because of the difficult to detect smaller crystalline particles in the HRTEM due to the strong lattice fringes of SiC. After reaction, the crystalline size of AlF₃ slightly increased to 9 nm (Fig. S6b). By contrast, this was increased from 6 to 13 nm for the AlF₃/C catalyst (Fig. S6c and d), suggesting that AlF₃ tends to sinter more significantly over AlF₃/C than over AlF₃/SiC, which agrees well with the results of XRD and EDX mapping.

The high dispersion of AlF₃ over SiC is not ascribed to its surface area. As indicated in Fig. S7, type-III adsorption isotherm and H3 hysteresis loop can be identified for SiC, suggesting that the surface texture was characteristic of a nonporous solid. Actually, the surface area of SiC estimated in the present study was only $1.4 \text{ m}^2/\text{g}$. However, the surface area of activated carbon is extremely high. A type-II adsorption isotherm and H4 hysteresis loop with specific surface area of ~1100 m²/g were found (Fig. S7b). Clearly, the distribution of AlF₃ is most likely attributed to the interaction between AlF₃ and SiC. Therefore, XPS experiments were further conducted for AlF₃/SiC and AlF₃/C catalysts to obtain deeper insight into the interactions of AlF₃ and its supports.

As shown in Fig. 3, compared with Al 2p in AlF_3/C , the binding energy in AlF_3/SiC decreases from 77.49 eV to 77.12 eV, shifting toward lower energy by 0.37 eV. Clearly, the strong Al–F bond is weakened over the SiC support. The shift indicates that F element of AlF_3 has been interacted with Si of SiC. This conclusion can be reinforced by the change of F 1 s binding energy. The binding energy of F in AlF_3/SiC (688.60 eV) is 0.45 eV higher than that in AlF_3/C (688.15 eV), which confirms the strong interaction between AlF_3 and SiC with F atoms. Moreover, this interaction can be further confirmed by the change in



Fig. 3. XPS spectra of fresh 5 wt% AlF_3/SiC and 5 wt% AlF_3/C for (a) Al 2p and (b) F 1 s.



Fig. 4. Conversion of HFC-152a over different catalysts as a function of time on stream (atmospheric pressure, 300 °C, GHSV of 300 h^{-1} , feed gas composition: 50 vol% HFC-152a and 50 vol% N₂).

chemical shift in AlF₃/SiC and AlF₃/C catalysts in the 27 Al-MAS NMR analysis (Fig. S8).

Unexpectedly, although SiC has low specific surface area, 5 wt% AlF₃/SiC shows high activity and stability for the dehydrofluorination of HFC-152a to form vinyl fluoride (VF). The catalytic activities over AlF₃/C, AlF₃/SiC and commercial SiC catalysts were evaluated at 300 °C, atmospheric pressure, and gas hourly space velocity (GHSV) of 300 h^{-1} . The conversion of HFC-152a as a function of time on stream (TOS) is illustrated in Fig. 4. Without AlF₃ loaded, SiC is rather inactive for the dehydrofluorination of HFC-152a. We suggest that the initial conversion over SiC corresponds to the etching of Si rather than real catalytic reaction (Table S1). The 5 wt% AlF₃/C catalyst exhibits moderate activity with significant deactivation for dehydrofluorination of HFC-152a. Clearly, strong Lewis acid catalyzes coke formation at the initial stage. After covering these type of Lewis acid sites, relatively stable activity could be achieved [14]. By contrast, 5 wt% AlF₃/SiC shows stable and much higher activity. As reported previously, small particle size for the active phase favors the improvement in activity and stability of dehydrofluorination catalysts [7].

Lower loading in AlF₃ over SiC support would result in lower activity (Fig. S9). However, due to the limited surface area of SiC, increase in the content of AlF₃ does not enhance the conversion of HFC-152a. With AlF₃ loading of 7.5 wt% and 10 wt%, almost identical conversions of HFC-152a were achieved. In addition, the performance of AlF₃ and AlF₃/SiC catalysts is compared in Fig. S10. As illustrated, 5 wt% AlF₃/SiC catalyst exhibits much higher reaction rate than that of AlF₃, MgF₂ and 5 wt% MgF₂/SiC. Clearly, AlF₃/SiC appears as a very promising catalyst for dehydrofluorination reactions.

4. Conclusions

Aluminum fluoride (AlF₃) supported on silicon carbide (SiC) was successfully synthesized as potential catalyst for practical dehydrofluorination reaction. As the dehydrofluorination involves the dissociation of C-F bond, large amount of reaction heat is required. With SiC as the support, its thermal conductivity facilitates the transfer of reaction heat to and from the supported catalytic phase. Consequently, less sintering of AlF₃ can be achieved compared with the AlF₃/C catalyst. Although its surface area is extremely low, the interaction between AlF₃ and SiC can contribute to the uniform dispersion of AlF₃. The catalytic performance of aluminum fluoride loaded on silicon carbide in the dehvdrofluorination of 1.1-difluoroethane to vinvl fluoride can be significantly higher than that of AlF₃ supported on activated carbon. The present results indicated that SiC is a potential and efficient support for catalysts of fluoroalkane dehydrofluorination. This study proposed a novel catalyst support (SiC) with high thermal conductivity and stability for the carrying strong endothermic catalytic reactions involving HFCs.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.catcom.2020.106033.

References

- P.M. Cox, R.A. Betts, C.D. Jones, S.A. Spall, I.J. Totterdell, Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model, Nature 408 (2000) 184–187.
- [2] G.J.M. Velders, D.W. Fahey, J.S. Daniel, M. McFarland, S.O. Andersen, The large contribution of projected HFC emissions to future climate forcing, Proc. Natl. Acad. Sci. U. S. A. 106 (2009) 10949–10954.
- [3] N. Abas, A.R. Kalair, N. Khan, A. Haider, Z. Saleem, M.S. Saleem, Natural and synthetic refrigerants, global warming: a review, Renew. Sust. Energ. Rev. 90 (2018) 557–569.
- [4] D.K. Papanastasiou, A. Beltrone, P. Marshall, J.B. Burkholder, Global warming potential estimates for the C-1-C-3 hydrochlorofluorocarbons (HCFCs) included in the Kigali amendment to the Montreal protocol, Atmos. Chem. Phys. 18 (2018) 6317–6330.
- [5] W.F. Han, J.C. Wang, L.L. Chen, L.T. Yang, S.C. Wang, M. Xi, H.D. Tang, W.C. Liu, W.Y. Song, J.J. Zhang, Y. Li, H.Z. Liu, Reverting fluoroform back to chlorodifluoromethane and dichlorofluoromethane: intermolecular cl/F exchange with chloroform at moderate temperatures, Chem. Eng. J. 355 (2019) 594–601.
- [6] W.F. Han, C.P. Zhang, H.L. Wang, S.L. Zhou, H.D. Tang, L.T. Yang, Z.K. Wang, Subnano MgF_2 embedded in carbon nanofibers and electrospun MgF_2 nanofibers by one-step electrospinning as highly efficient catalysts for 1,1,1-trifluoroethane dehydrofluorination, Catalysis Science & Technology 7 (2017) 6000–6012.
- [7] B. Liu, W.F. Han, X.L. Li, L.C. Li, H.D. Tang, C.S. Lu, Y. Li, X.N. Li, Quasi metal organic framework with highly concentrated Cr₂O₃ molecular clusters as the efficient catalyst for dehydrofluorination of 1,1,1,3,3-pentafluoropropane, Appl. Catal B-Environ. 257 (2019) 117939.
- [8] J.K. Murthy, U. Gross, S. Rudiger, E. Unveren, E. Kemnitz, Mixed metal fluorides as doped Lewis acidic catalyst systems: a comparative study involving novel high surface area metal fluorides, J. Fluor. Chem. 125 (2004) 937–949.
 [9] H.D. Tang, M.M. Dang, Y.Z. Li, L.C. Li, W.F. Han, Z.J. Liu, Y. Li, X.N. Li, Rational
- [9] H.D. Tang, M.M. Dang, Y.Z. Li, L.C. Li, W.F. Han, Z.J. Liu, Y. Li, X.N. Li, Rational design of MgF₂ catalysts with long-term stability for the dehydrofluorination of 1,1difluoroethane (HFC-152a), RSC Adv. 9 (2019) 23744–23751.
- [10] J. Wang, Y.F. Lu, H.L. Yuan, Effects of plasticizers and stabilizers on thermal stability of polyvinyl fluoride, Polym.-Plast. Technol. Eng. 46 (2007) 461–468.
- [11] W.F. Han, B. Liu, X.L. Li, L.T. Yang, J.C. Wang, H.D. Tang, W.C. Liu, Combustion synthesis of amorphous Al and Cr composite as the catalyst for Dehydrofluorination of 1,1-Difluoroethane, Ind. Eng. Chem. Res. 57 (2018) 12774–12783.

- [12] A.W. Baker, D. Bonniface, T.M. Klapotke, I. Nicol, J.D. Scott, W.D.S. Scott, R.R. Spence, M.J. Watson, G. Webb, J.M. Winfield, Catalytic fluorination of trichloroethene by anhydrous hydrogen fluoride in the presence of fluorinated chromia under static conditions, J. Fluor. Chem. 102 (2000) 279–284.
- [13] W.Z. Jia, Q. Wu, X.W. Lang, C. Hu, G.Q. Zhao, J.H. Li, Z.R. Zhu, Influence of Lewis acidity on catalytic activity of the porous alumina for Dehydrofluorination of 1,1,1,2-Tetrafluoroethane to Trifluoroethylene, Catal. Lett. 145 (2015) 654–661.
- [14] X.X. Fang, Y. Wang, W.Z. Jia, J.D. Song, Y.J. Wang, M.F. Luo, J.Q. Lu, Dehydrofluorination of 1, 1, 1, 3, 3-pentafluoropropane over C-AlF₃ composite catalysts: improved catalyst stability by the presence of pre-deposited carbon, Applied Catalysis a-General 576 (2019) 39–46.
- [15] D.J. Sung, D.J. Moon, S. Moon, J. Kim, S.I. Hong, Catalytic pyrolysis of chlorodifluoromethane over metal fluoride catalysts to produce tetrafluoroethylene, Appl. Catal. A-Gen. 292 (2005) 130–137.
- [16] K. Watari, Evaluation of thermal conductivity of grains and fillers by using thermoreflectance technique-Si₃N₄, AlN, SiC, Journal of the Ceramic Society of Japan 122 (2014) 967–970.
- [17] U. Baig, M.A. Gondal, M.A. Ansari, S. Akhtar, Facile synthesis, characterization and antibacterial activity of nanostructured palladium loaded silicon carbide, Ceram. Int. 44 (2018) 16908–16914.
- [18] L. Li, J. Zheng, Y.F. Liu, W. Wang, Q.S. Huang, W. Chu, Impacts of SiC carrier and nickel precursor of NiLa/support catalysts for CO₂ selective hydrogenation to synthetic natural gas (SNG), ChemistrySelect 2 (2017) 3750–3757.
- [19] Y.B. Wang, X.N. Guo, M.Q. Lu, Z.Y. Zhai, Y.Y. Wang, X.Y. Guo, Cu₂O/SiC as efficient

catalyst for Ullmann coupling of phenols with aryl halides, Chin. J. Catal. 38 (2017) 658–664.

- [20] H. Ba, J.J. Luo, Y.F. Liu, D.V. Cuong, G. Tuci, G. Giambastiani, J.M. Nhut, N.D. Lam, O. Ersen, D.S. Su, P.H. Cuong, Macroscopically shaped monolith of nanodiamonds @ nitrogen-enriched mesoporous carbon decorated SiC as a superior metal-free catalyst for the styrene production, Applied Catalysis B-Environmental 200 (2017) 343–350.
- [21] M. Zhong, Y.Y. Guo, J.G. Wang, Z.C. Ma, M. Xia, C.B. Chen, L.T. Jia, B. Hou, D.B. Li, The Fischer-Tropsch synthesis performance over cobalt supported on silicon-based materials: the effect of thermal conductivity of the support, Catalysis Science & Technology 9 (2019) 3482–3492.
- [22] Z.H. Liu, Q. Qi, Y.J. Yan, H. Zhang, X.J. Liu, H.J. Luo, Z.R. Huang, Effect of residual phase and grain size on corrosion resistance of SiC ceramics in mixed HF-HNO₃ acid solution, J. Inorg. Mater. 31 (2016) 661–666.
- [23] A. Klegova, A. Inayat, P. Indyka, J. Grybos, Z. Sojka, K. Pacultova, W. Schwieger, A. Volodarskaja, P. Kustrowski, A. Rokicinska, D. Fridrichova, L. Obalova, Cobalt mixed oxides deposited on the SiC open-cell foams for nitrous oxide decomposition, Appl. Catal. B-Environ. 255 (2019).
- [24] D. Dambournet, G. Eltanamy, A. Vimont, J.-C. Lavalley, J.-M. Goupil, A. Demourgues, E. Durand, J. Majimel, S. Rudiger, E. Kemnitz, J.M. Winfield, A. Tressaud, Coupling sol-gel synthesis and microwave-assisted techniques: a new route from amorphous to crystalline high-surface-area aluminium fluoride, Chem. Eur. J. 14 (2008) 6205–6212.